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Beck (1988) reported that the outputs of 2D Gabor filters can account for much of the segregation of a periodic visual display (tripartite pattern) into regions. We have conducted a series of experiments showing that grouping processes, as well as the outputs of spatial-frequency/orientation channels, yield automatic spontaneous segregation. In our tripartite patterns, the arrangement of local properties is different in different regions so that if the display is suitably filtered by convolving the appropriate property at each point, or by performing some equivalent filtering process in the Fourier domain, the regions in the filtered display differ in different regions. We have shown that this type of computation is not able to account for the spontaneous segregation of a line in a display of disconnected shapes. A striking finding reported by Beck (1988) was that squares differing by a large lightness difference sometimes failed to give region segregation in a tripartite pattern while the same pattern of squares differing by a smaller lightness differences yielded strong region segregation. We conducted experiments comparing the segregation

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of a tripartite pattern into regions and the segregation of a pattern composed of two interspersed populations into subpopulations. Perceived lightnesses are the same for a given set of squares whether they are in texture regions or in intermixed populations. Perceived population segregation is approximately a single-valued function of the lightness differences of the squares but perceived region segregation is not. Perceived region segregation is approximately a singe-valued function of the ratio of the contrasts of the light and dark squares as long as we avoid the nonlinearities introduced by light adaptation.

VISUAL PROCESSING IN TEXTURE SEGREGATION

Annual Report AFOSR Grant 88-0323
(September 1, 1988 - September 30, 1989)

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CONTENTS

1. ABSTRACT

Beck (1988) reported that the outputs of 2D Gabor filter can account for much of the segregation of a periodic visual display (tripartite pattern) into regions. Two nonlinearities were shown also to occur. One nonlinearity was an intensity dependent nonlinearity which can be accounted for by sensory adaptation occurring before the channels or by a compressive intracortical interaction among the channels. The second nonlinearity was a rectification-like nonlinearity that is like that presumed to occur in complex cells (Spitzer & Hochstein, 1988).

We have conducted a series of experiments showing that grouping processes, as well as the outputs of spatial-frequency/orientation channels, yield automatic spontaneous segregation. In a display composed of disconnected shapes, a line may spontaneously segregate even though the shapes in the line do not differ from the other shapes in the display. The spacing between the shapes in the line and in the background are also similar. The difference is that the shapes in the line are approximately aligned, their spacing is regular and there is a greater density of shapes in the direction of the line. In our tripartite patterns, the arrangement of local properties is different in different regions so that if the display is suitably filtered by convolving the appropriate property at each point, or by performing some equivalent filtering process in the Fourier domain, the regions in the filtered display differ in different regions. We have shown that this type of computation is not able to account for the spontaneous segregation of a line in a display of disconnected shapes. Spatial-frequency mechanisms and element linking processes differ in the way they are affected by stimulus variables. There is a trade-off between area and contrast when perceived segregation depends on differences in the outputs of spatial frequency channels. Perceived segregation is also not affected by edge misalignment. Alternatively, when perceived segregation depends on element linking, edge length and edge misalignment are important. There is also no contrast x area tradeoff.

A striking finding reported by Beck (1988) was that squares differing by a large lightness difference sometimes failed to give region segregation in a tripartite pattern while the same pattern of squares differing by a smaller lightness differences yielded strong region segregation. The functions describing the perceived lightness differences of the squares and the perceived segregation of the tripartite patterns are not the same functions. We conducted experiments comparing the segregation of a tripartite pattern into regions and the segregation of a pattern composed of two interspersed populations into subpopulations. Perceived lightnesses are the same for a given set of squares whether they are in texture regions or in intermixed populations. Perceived population segregation is approximately a single-valued function of the lightness differences of the squares but perceived region segregation is not. Perceived region segregation is approximately a singe-valued function of the ratio of the contrasts of the light and dark squares as long as we avoid the nonlinearities introduced by light adaptation. The reason for this difference is that the detectors showing strikingly different outputs to the different arrangement of squares in the striped and checked regions have large receptive fields that are sensitive to the fundamental frequency of the texture region. They respond to the periodicity of the pattern and signal differences in the overall pattern of squares in the striped and checked regions of the tripartite pattern. Population segregation can not be due to differences in the response of the large bar detectors; because the light and dark squares are distributed throughout the display, so the excitatory and inhibitory regions of the large bar detectors fall on both dark and light squares. A plausible mechanism is to suppose that the visual system detects bimodality with respect to a feature such as lightness and divides the original population into two subpopulations.

2. RESEARCH SUMMARY

2.1 Line Segregation

Seven experiments investigated the properties of the line elements that affect line segregation. Experiments 5a, 5b and 6 were conducted during the period of this report. The other experiments were conducted prior to the report period. They were written up for publication during the report period and have been included for completeness. Experiment 1 shows that edge straightness, element elongatedness, and principal axis orientation affect line segregation. Experiment 2 demonstrates that lateral displacement of the elements affects line segregation and that the effect varies with the scale of the stimulus, implying that it is not due to spatial density. Experiment 3 shows that line segregation is not significantly different for solid elements and outline elements in spite of the fact that their spatial densities scaled differently. Experiment 4 shows that line segregation is relatively insensitive to the contrast of the elements (above some minimum value), but that it is sensitive to element edge length, even when areal contrast (area x contrast) is equalized. Experiments 5a and 5b show that elements composed of subelements having opposite signs of contrast averaging to the background luminance yielded line segregation as good as those produced by solid elements when the absolute contrasts of the elements or subelements was high. Sutter, Beck & Graham (1989) proposed a model based on Gabor filters to explain the perceived segregation of tripartite patterns. A principal purpose of the experiments was to test whether this type of model can explain line segregation. Experiment 6 shows that the outputs of Gabor filters fail to account for line segregation. Taken together, the results of these experiments indicate strongly that other factors in addition to spatial density such as the alignment of element edges and edge length influence line segregation. Possible models of line segregation based on element grouping, feature density and search are briefly discussed.

2.1.1 *Introduction*

In a display composed of disconnected elements such as bars, blobs, dots, etc., one often perceives the display as spontaneously segregated into groups of elements. Julesz (1962), Beck (1966), and many others (e.g. Olson & Attneave, 1970) have studied examples of this phenomenon in which the groups of elements constitute regions. Beck (1967; 1972) has studied examples in which the elements of the groups are randomly interspersed; in this case, the display segregates into interspersed subpopulations, not into regions. Treisman (Treisman & Gormican, 1988) studied spontaneous "popout" of a single element in a pattern of distractor elements. In this paper, we will be concerned with a class of examples in which the elements segregate into a line-like pattern on a background of distractors. This phenomenon is illustrated in Figure 1, which shows a dot pattern in which the horizontal line of dots in the center is perceived immediately and effortlessly. The individual dots in the line are identical to the dots in the background. Possible factors contributing to the segregation of the dots that lie on the line are the increased density in the direction of the line, alignment, and the regularity of their spacing and their collinearity (Smits, Vos & Van Oeffelen, 1985; Uttal,1975).

Method

Stimuli.--The stimuli were computer generated and displayed on either the Lisp Machine console (Experiments 1-2), or on a Tektronix RGB monitor (Experiments 3-5). A trial consisted

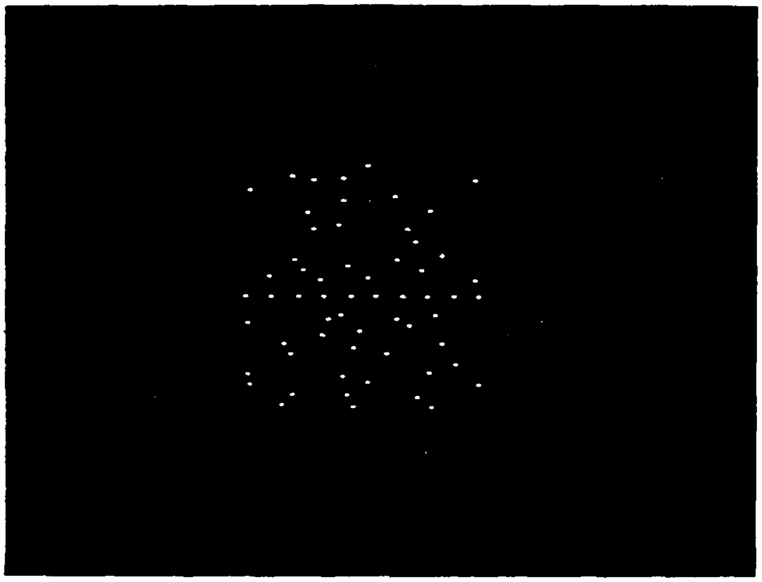


Figure 1.

of a randomly generated pattern of distractor elements in the center of which was a vertical or horizontal line composed of disconnected elements. The elements composing the line were always equally spaced. Half of the displays contained a horizontal line and half a vertical line. All spacings were contour-to-contour separations. The smallest possible separation between distractors and between distractors and line elements was the same. The spacings of the elements in the line, their number, the number of distractors in the background, their smallest possible separation from each other and from the line elements, and the luminances of the background and of the distractors and of the line elements are given in the descriptions of the individual experiments. Except for Experiment 4, the stimuli were viewed from a distance of 1.83 m. with a pixel subtending approximately 33 sec of arc. on the Lisp Machine console and approximately 1.08 min of arc on the RGB monitor. In Experiment 4, the stimuli were viewed from a distance of 3.15 m. and a pixel subtended 38 sec of arc. The Lisp machine console was masked with flat black cardboard that restricted a subject's view to the stimulus display. The experiments were conducted in a dimly illuminated room.

Procedure.--For each stimulus presentation, a subject responded whether the line was vertical or horizontal. Reaction times and errors were recorded by the computer. Subjects were instructed to depress the left response button to indicate a horizontal line and the right response button to indicate a vertical line. The instructions were to respond as quickly as possible while minimizing errors. Stimulus exposures were 150 msec except in Experiments 5a and 5b where they were 300 msec. Each stimulus was preceded by a fixation "X" for 2 sec. and followed immediately by a pattern mask that was terminated by a subject's response. Two seconds following termination of the mask, the fixation "X" reappeared and the next trial was initiated. Throughout an experiment, including intervals during which the screen was blank, the background luminance of the screen remained constant at the value of the background for the stimuli in that experiment. Before beginning an experiment, subjects were shown each of the different stimulus displays for 2 sec. All subjects were then given a practice block of trials at the exposure duration used in the experiment. The practice block was followed by three experimental blocks. In the practice block, each stimulus was presented twice and in the experimental blocks, each stimulus was presented five times. Thus, each subject made 15 responses to each stimulus. Within each block, the stimuli were presented in a random order subject to the restriction that all stimuli were presented before a stimulus was repeated. Subjects who made more than 10 percent errors in the easiest condition of an experiment were replaced. Subjects were naive about the purposes of an experiment and were paid to participate. Ten different subjects served in each experiment. All had normal or corrected to normal vision.

Data analysis.--Mean reaction times and total errors for each subject were analyzed in separate within subjects analyses of variance. Differences significant at the 5 percent level or higher are reported. The figures shown plot the mean of the 10 subjects' mean reaction times and total errors. Only correct responses were averaged in calculating mean reaction times. Reaction times greater than 2500 msec were also not averaged. The mean reaction times for a subject were based on 30 responses per stimulus (15 with the line vertical and 15 with the line horizontal) minus errors and the responses that took longer than 2500 msec. Total errors for a subject were based on 30 responses per stimulus minus the too long responses. Too long responses were extremely rare. Subjects' reaction times and errors to vertical and horizontal lines did not differ significantly. Similar results have been reported by Uttal (1975) and Smits, Vos, & Oeffelen (1985). Errors and reaction times also exhibited similar trends. That is, conditions with longer reaction times had higher error rates indicating that subjects did not trade accuracy for speed.

2.1.3 *Experiment 1: Bars and Blobs*

In this experiment, ten stimuli were presented and three variables were investigated. One variable was whether the edges of the elements were straight (bars) or irregular (blobs). Figure 2 shows the bar and blob shapes. The edges of the bars in the line were collinear. The blobs had no straight edges that could align. The blobs were derived from the bars by adding and subtracting pixels from the boundary. The numbers of pixels in the bars and blobs were the same. A second variable was the elongatedness (aspect ratio) of the elements. The aspect ratios of the bars were 1.0 (12 x 12 pixels), 1.8 (9 x 16 pixels), and 2.3 (8 x 18 pixels). The bar with an aspect ratio of 1.0 was square and the blob was circular. The third variable was the alignment of the principal axes of the elements with the line. With the 1.8 and 2.3 aspect ratios, the principal axes of the elements could either be collinear with the line or orthogonal to the line. The bars and blobs composing the vertical lines in Figures 3a and 3b have an aspect ratio of 2.3 and principal axes orthogonal to the line. The distances between the elements in the line was always 24 pixels. In the collinear displays, a line was composed of 10 elements. In the orthogonal displays, a line was composed of 13 elements when the aspect ratio was 1.8 and 14 elements when the aspect ratio was 2.3. The number of distractors was 160. The smallest possible separation between distractors was 4 pixels. The luminance of the background was 56.5 cd/m^2 and of the line elements and distractors .62 cd/m^2.

Figures 4a and 4b show the mean reaction times and the mean total errors. The main effect of aspect ratio was significant. For both reaction times and errors, the bar and blob means decreased markedly with an increase in aspect ratio from 1.0 to 1.8. There was also a significant interaction between element shape and element orientation for both reaction times and errors. Lines composed of bars were detected more rapidly and with fewer errors than lines composed of blobs when the directions of their principal axes were the same as the direction of the line (collinear arrangement). Lines composed of blobs were detected more rapidly and with fewer errors than lines composed of bars when the directions of their principal axes were orthogonal to the line (crthogonal arrangement). The straight edges of the bars facilitated line segregation when collinear with the line but interfered with line segregation when orthogonal to the line. From a density standpoint, bars and blobs are essentially the same, but, as this experiment shows, they behave quite differently when aspect ratio and axis orientation are varied. This clearly implicates edge alignment, which exists for bars and not for blobs, as an important factor in line segregation.

2.1.4 *Experiment 2: Collinear and Misaligned Squares.*

This experiment studied the effect of stimulus scale (magnification) when the elements were collinear (aligned) or laterally displaced (misaligned). The square size, the spacing between the squares in the line, and the lateral displacement of the misaligned squares were all increased proportionally. The square sizes were 8, 16, 24 and 32 pixels on a side. Alternate squares were laterally displaced by 3, 6, 9 and 12 pixels, .375 of the side of a square. Figures 5a and 5b show displays with the squares aligned and misaligned. The smallest possible separation between distractors was 1, 2, 3 and 4 pixels, respectively. The number of squares in the line was 11 and the number of distractors 100. The luminance of the background was 56.5 cd/m^2 and of the line elements and distractors .62 cd/m^2.

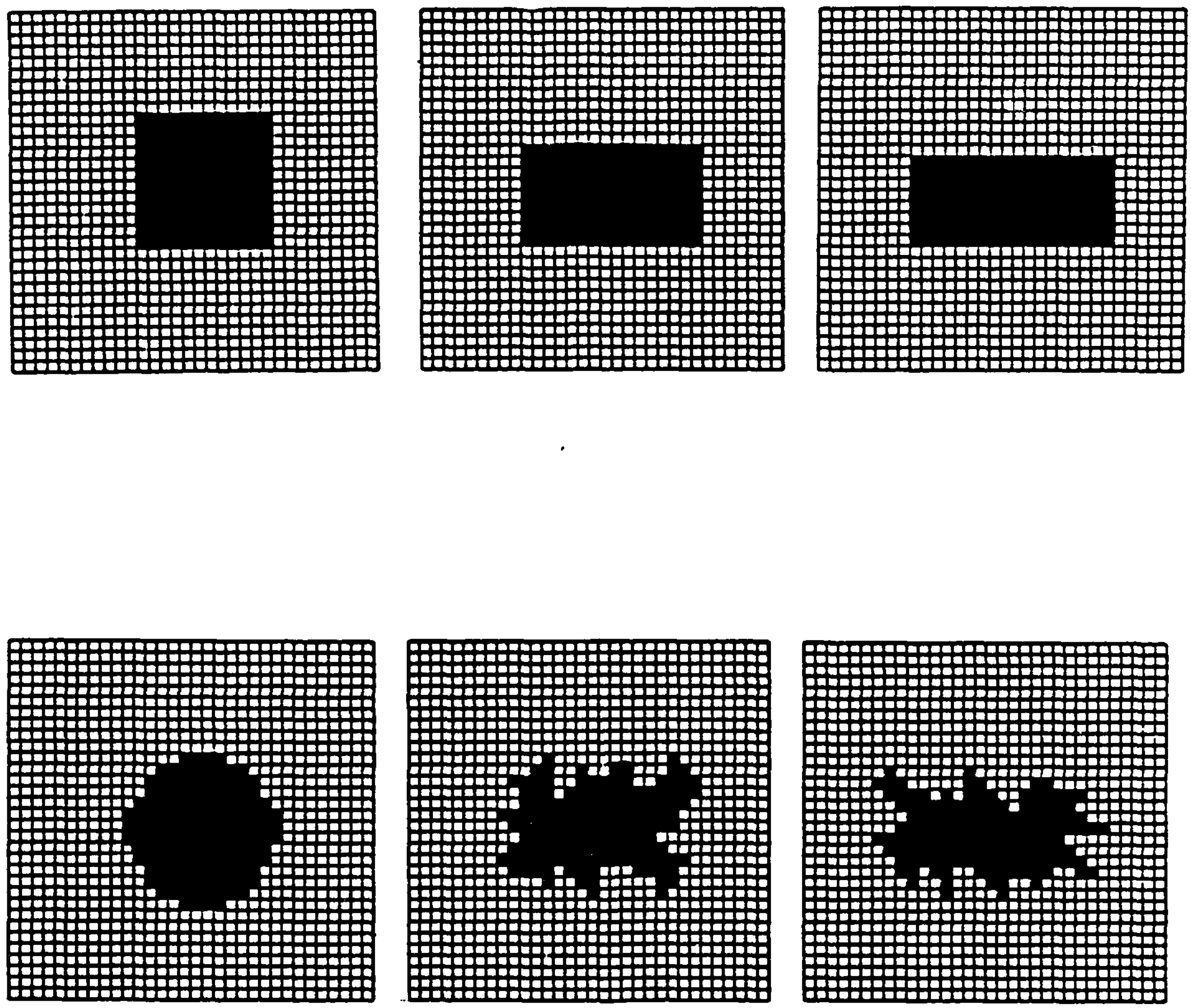
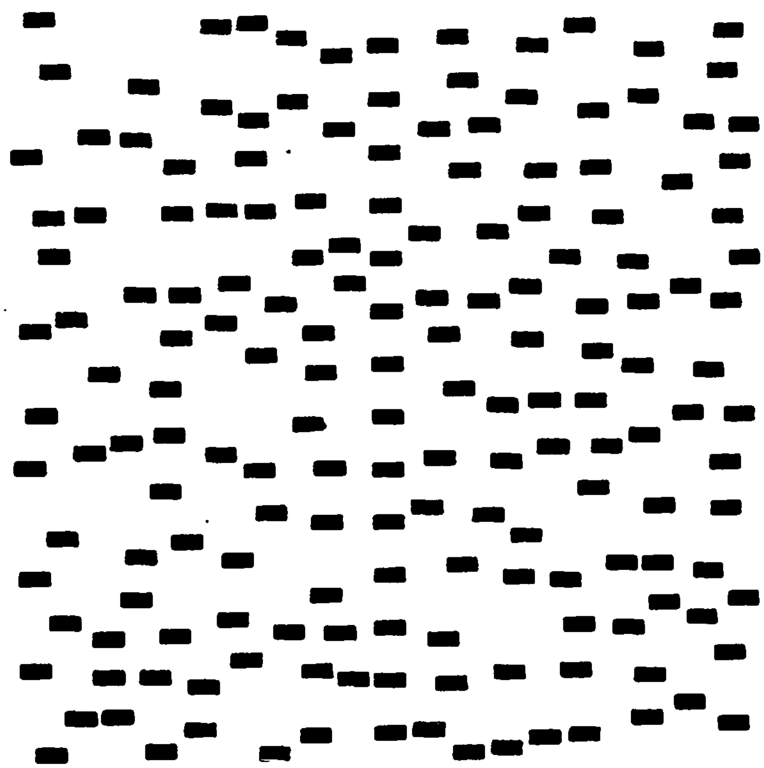
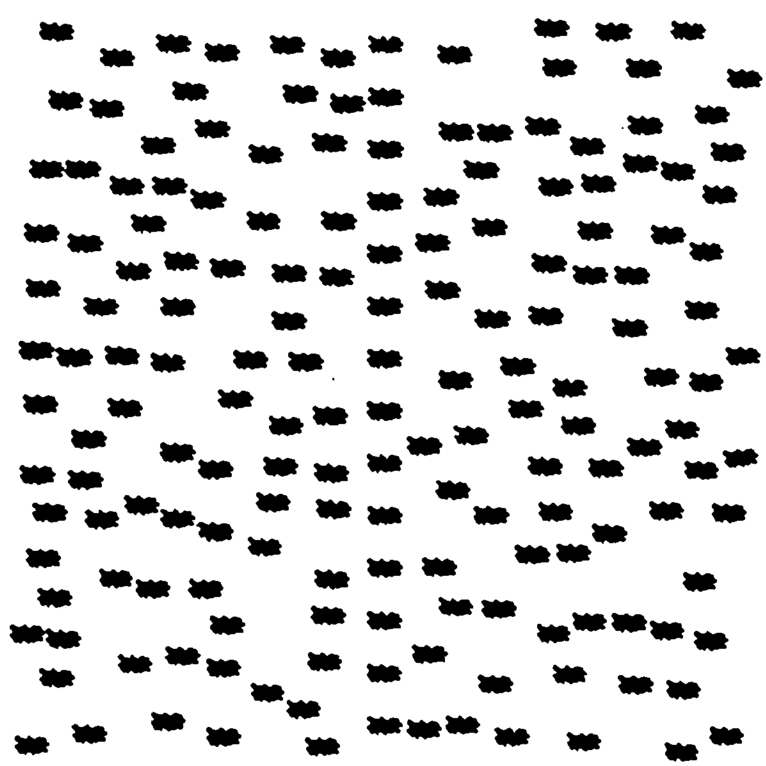


Figure 2.

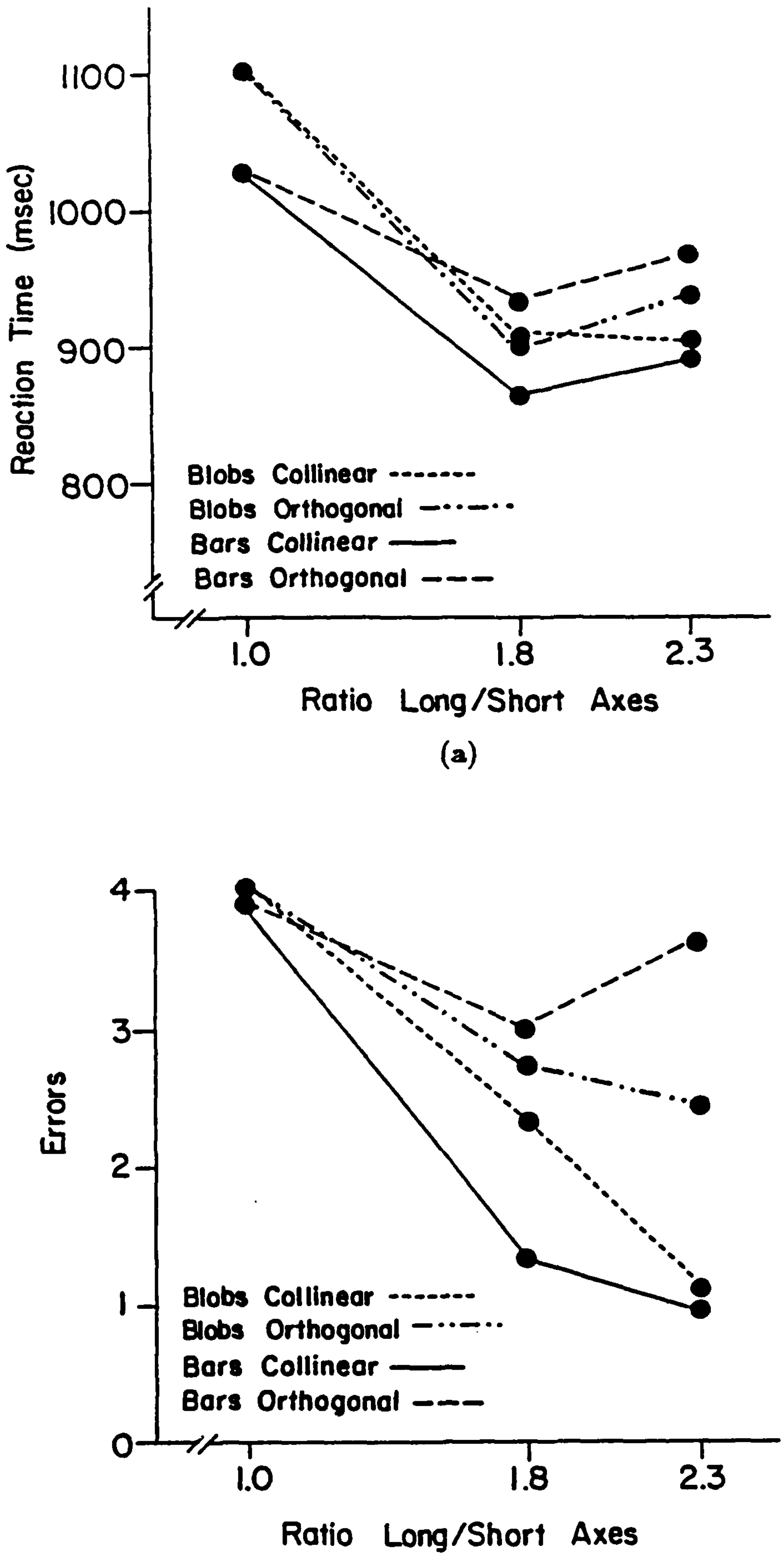


(a)



(b)

Figure 3.



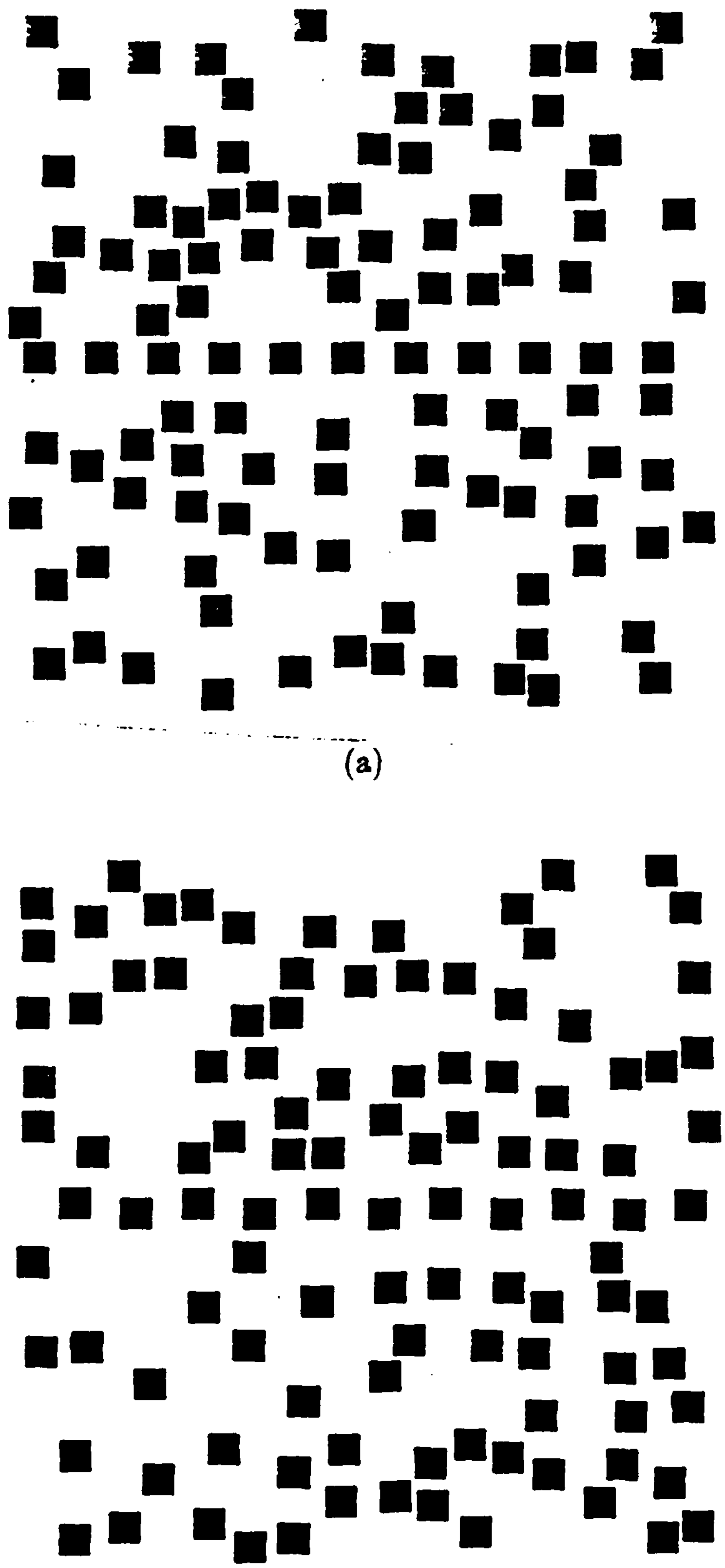
Reaction Time (msec)
1100
1000
900
800
1.0
1.8
2.3
Ratio Long/Short Axes
Blobs Collinear
Blobs Orthogonal
Bars Collinear
Bars Orthogonal

(a)

Errors
4
3
2
1
0
1.0
1.8
2.3
Ratio Long/Short Axes
Blobs Collinear
Blobs Orthogonal
Bars Collinear
Bars Orthogonal

(b)

Figure 4.



(a)

(b)

Figure 5.

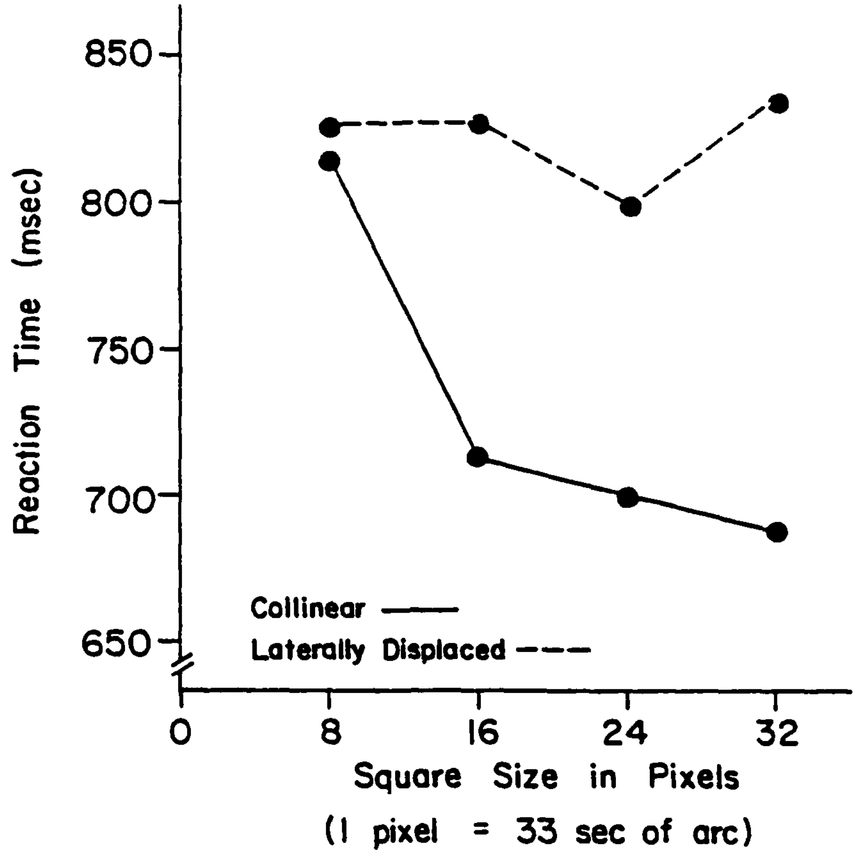
Figures 6a and 6b show the mean reaction times and mean total errors. There is a marked difference between the results for the aligned and misaligned squares. For the misaligned squares, both the reaction times and errors remained constant as a function of square size. For the aligned squares, the reaction times and errors decreased with increasing square size. The differences between the aligned and misaligned squares were significant for both reaction times and errors. Figures 6a and 6b show that both reaction times and errors decreased markedly for the aligned squares when square size increased from 8 (4.4 minutes) to 16 pixels (8.8 minutes) on a side. There was a significant interaction between alignment (collinear vs laterally displaced) and square size for reaction times but not for errors.

If line segregation were solely dependent on the density of elements in a particular direction, reaction time would be expected to remain constant if size and spacing are increased proportionally. In fact, however, for the aligned squares, the reaction times and errors decreased with increasing square size and spacing of the squares. This suggests that increased edge alignment facilitated detecting the line.

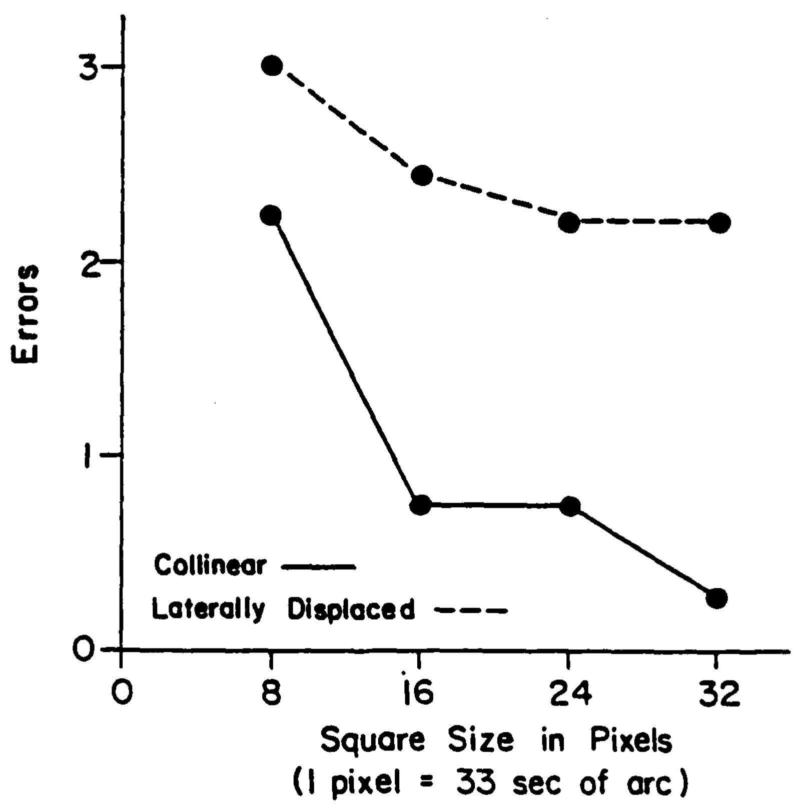
2.1.5 *Experiment 3: Solid and Outline Squares.*

In this experiment, eight stimuli were used. Six stimuli were solid and outline squares, 10 pixels on a side, separated by 10, 20, and 30 pixels. The number of distractors were 80, 120 and 160, respectively. The number of elements in the line was 10. The smallest possible separation between distractors was 4, 6, and 8 pixels, respectively. Two additional stimuli were outline and solid squares, 20 pixels on a side, separated by 20 pixels. The stimuli were a 2x scaling of the stimuli with a 10 pixel square and a 10 pixel separation. The luminance of the background was 109.6 cd/m^2 and of the outlines and solid squares .058 cd/m^2. Figures 7a and 7b show 10 pixel outline and solid squares separated by 10 pixels. Figures 8a and 8b show the mean reaction times and mean total errors when the 10 pixel squares were separated by 10, 20, and 30 pixels. The results for the outline and solid squares were similar. The only significant effect was the spatial separation of the squares. Mean reaction times and mean total errors increased with increased spatial separation. Figures 9a and 9b show the mean reaction times and mean total errors for the 10 and 20 pixel squares with 10 and 20 pixel separations. Differences in reaction times and errors between the outline and solid squares were not significant. For both solid and outline squares, decreases in reaction times with scaling were significant while the decreases in errors were not significant.

Since the thickness of the outline remained constant, rescaling of the stimuli had different effects on the spatial densities of the solid and outline squares. With rescaling the number of pixels in a solid square increases quadratically while that in an outline square only increases linearly. In this experiment, however, the effects of rescaling were the same for the solid and outline squares. The similarity in results for outline and solid squares suggests that density is not the principal factor in line segregation. As with the aligned squares in Experiment 2, the decrease in reaction time for outline and solid squares with scaling indicates the importance of edge length.

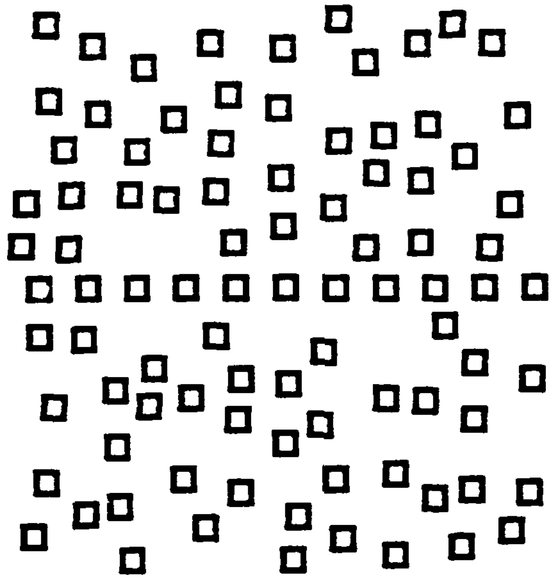

850
800
750
700
650
Reaction Time (msec)
Collinear
Laterally Displaced
0
8
16
24
32
Square Size in Pixels
(1 pixel = 33 sec of arc)

(a)

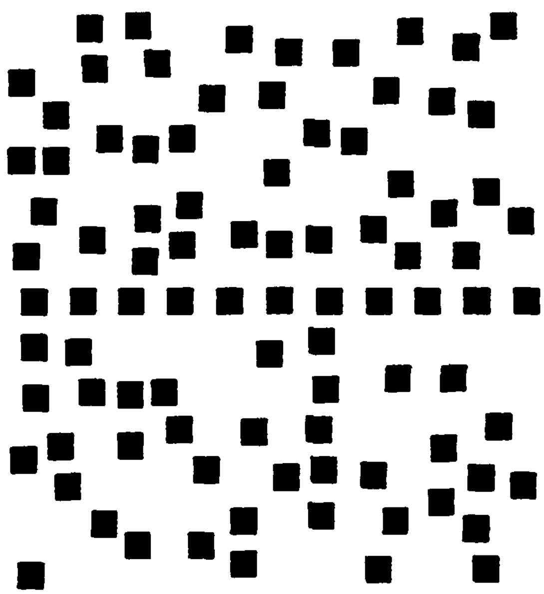

3
2
1
0
Errors
Collinear
Laterally Displaced
0
8
16
24
32
Square Size in Pixels
(1 pixel = 33 sec of arc)

(b)

Figure 6.

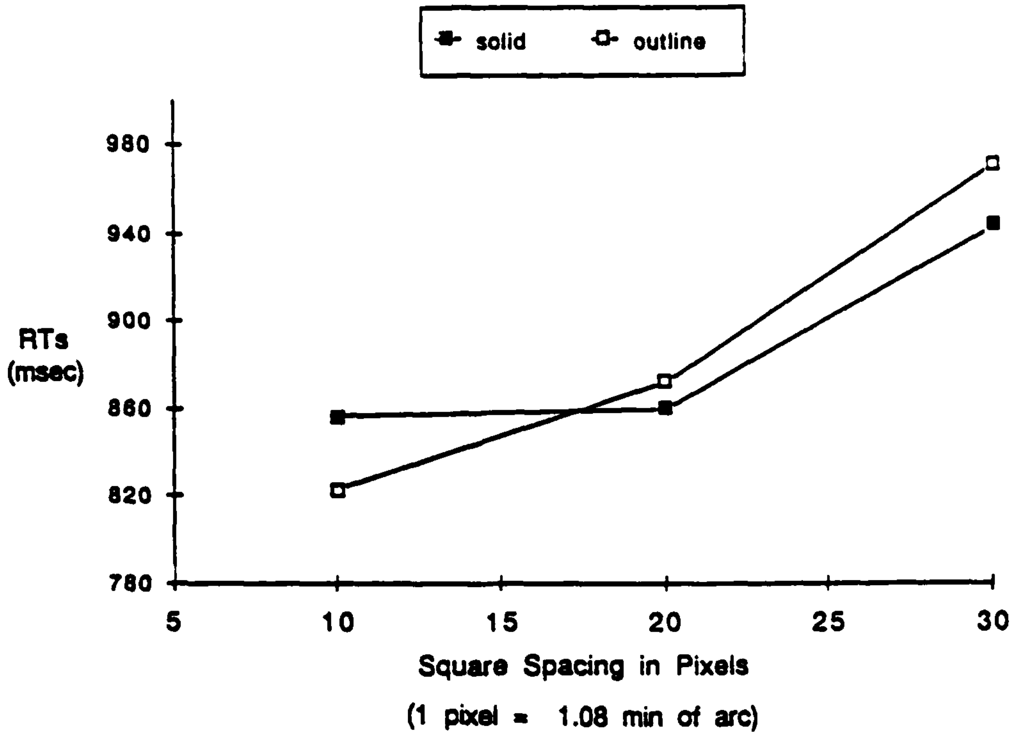


(a)



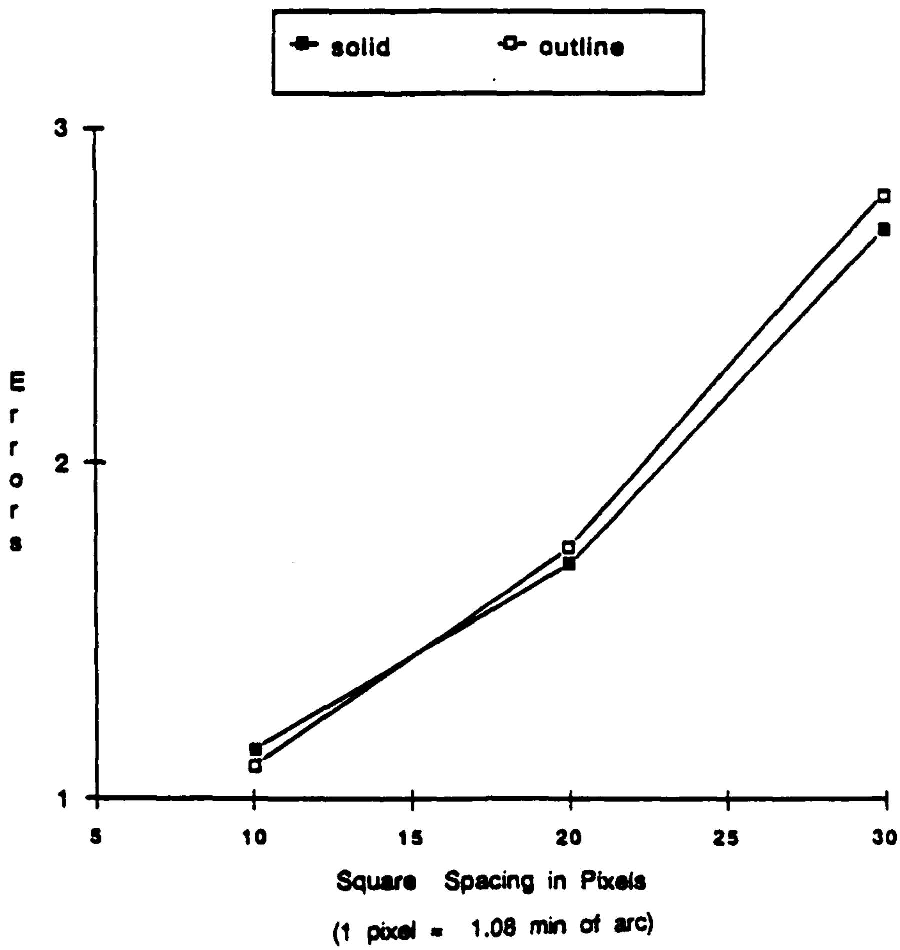
(b)

Figure 7.



solid
outline
RTs (msec)
980
940
900
860
820
780
5
10
15
20
25
30
Square Spacing in Pixels
(1 pixel = 1.08 min of arc)

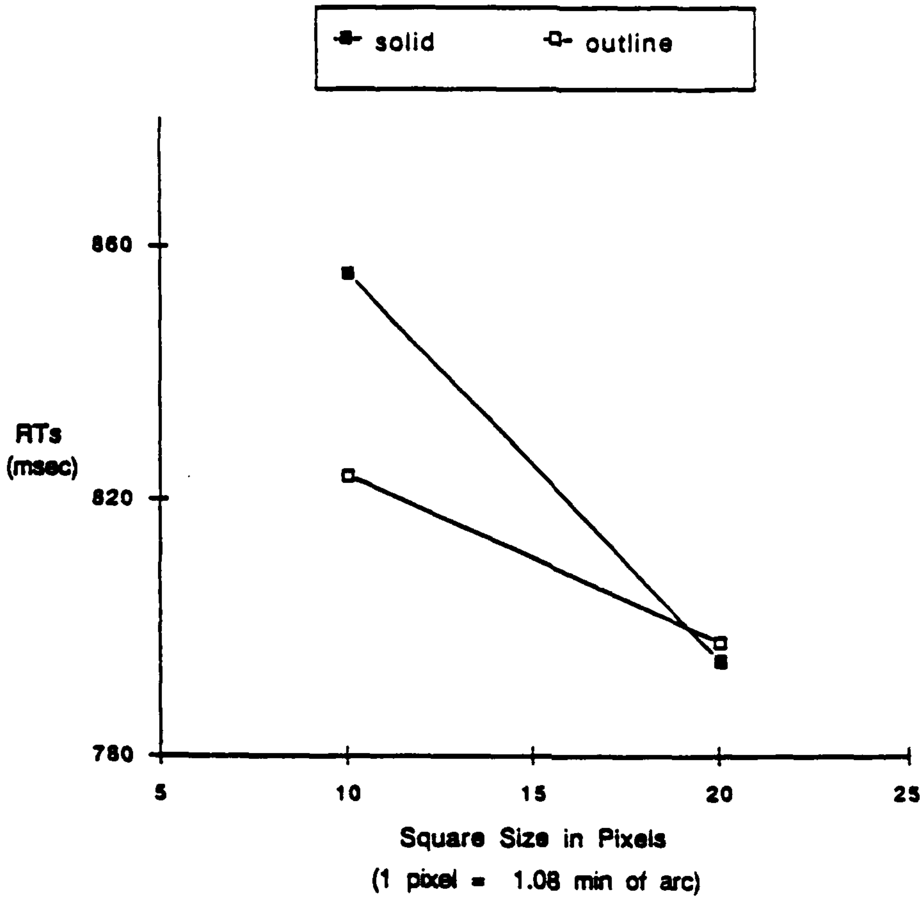
(a)



solid
outline
Errors
3
2
1
5
10
15
20
25
30
Square Spacing in Pixels
(1 pixel = 1.08 min of arc)

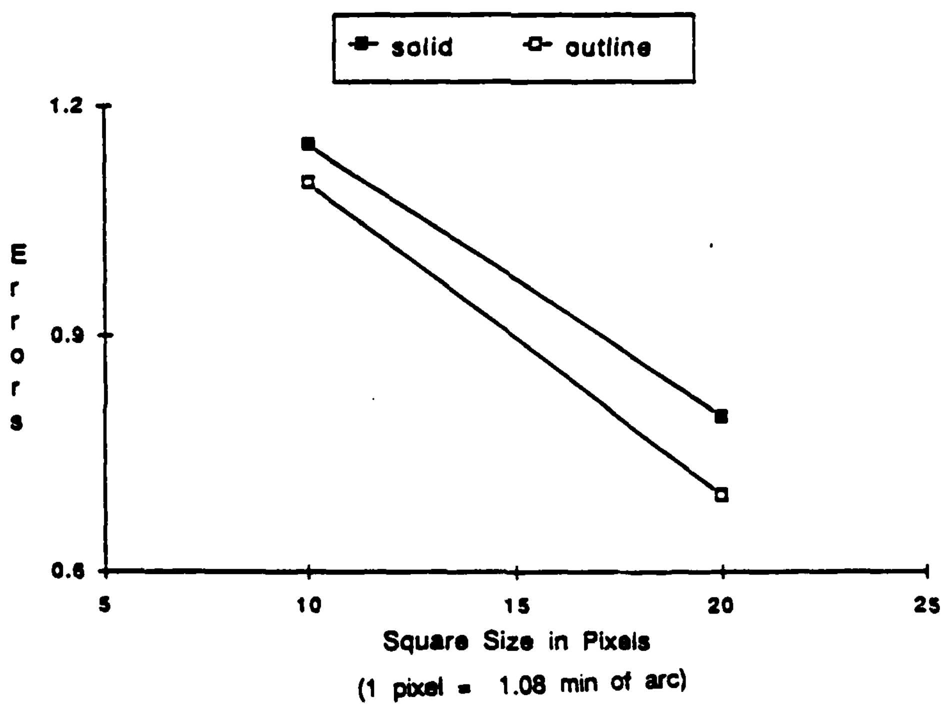
(b)

Figure 8.



solid
outline
860
820
780
RTs
(msec)
5
10
15
20
25
Square Size in Pixels
(1 pixel = 1.08 min of arc)

(a)



solid
outline
1.2
0.9
0.6
Errors
5
10
15
20
25
Square Size in Pixels
(1 pixel = 1.08 min of arc)

(b)

Figure 9.

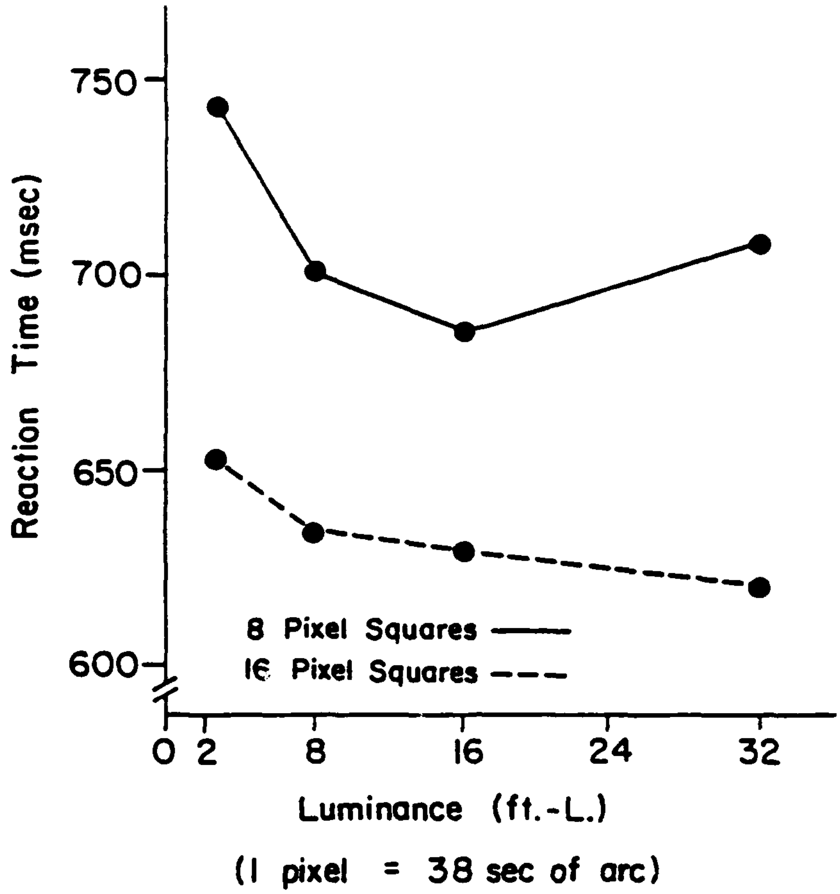
2.1.6 *Experiment 4: Area x Contrast.*

This experiment investigated the effects of element contrast on line segregation. Four contrasts and two square sizes gave eight stimuli. The squares were 8 and 16 pixels on a side. The displays with the 16 pixel squares were a 2x scaling of the displays with the 8 pixel squares. The number of squares in the line was 10 and the number of distractors 80. The separations between squares in the line were 12 and 24 pixels, respectively. The smallest possible separations between distractors were 6 and 12 pixels, respectively. Contrast was increased by increasing the luminances of the squares against a uniform background of .058 cd/m^2. The luminances of the squares were 6.85, 27.4, 54.8, and 109.6 cd/m^2. (Plotted in Figures 10a and 10b as 2, 8, 16, and 32 ft.-L.) Figures 10a and 10b show the mean reaction times and mean total errors. The main effect of square size was significant for both reaction times and errors. As with the aligned squares in Experiment 2, the larger squares were segregated more strongly and with fewer errors than the smaller squares. This occurred at all luminance levels even when the areal contrast (area x contrast) of the 8 pixel square was four times the areal contrast of the 16 pixel squares. Line segregation did not increase with areal contrast arguing against segregation being based on density differences. Edge length appears to be more important than areal contrast for line segregation.

One possible confounding factor is the effect of the contrast sensitivity function. Contrast sensitivity is generally highest at spatial-frequencies ranging from 2-8 cycles/degree, depending on experimental conditions (Graham, 1989). The 8 pixel square had a spatial frequency of 6 cycles/degree and the 16 pixel square a spatial frequency of 3 cycles/degree. Though the ratio of the areal contrast of the small square (with a luminance of 110.4 cd/m^2.) to that of the large square (with a luminance of 6.9 cd/m^2.) was 4:1, it is possible that greater sensitivity at 3 cycles/deg might be the basis for the stronger line segregation of the large squares. Experiment 4 in Sutter, Beck & Graham (1989), however, indicates that maximum sensitivity for the conditions of the present experiment with an exposure duration of 1000 msec is approximately 5.6 cycles/degree. Although the effect of duration on spatial tuning is not completely clear, a recent study indicates that above threshold temporal integration is essentially the same at 3 and 6 cycles/degree (Georgeson, 1987). It is therefore unlikely that greater contrast sensitivity to the 16 pixel square (3 cycles/degree) would offset the greater areal contrast of the 8 pixel square (6 cycles/degree). The similarity in results for the outline and solid squares also suggests that the greater segregation of the larger squares is not due to the greater sensitivity to frequencies at 3 cycles/degree.

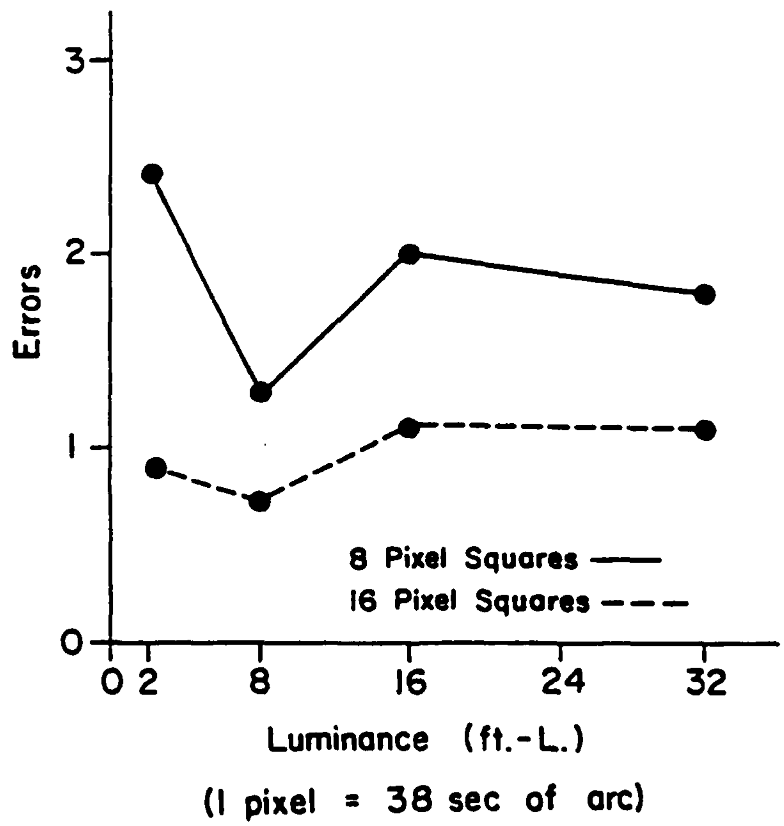
2.1.7 *Experiments 5a and 5b Laplacian Squares.*

These experiments compared the detection of a line composed of solid squares with that of a line composed of squares made up of checks (small subsquares) whose luminances average out to the luminance of the background (Laplacian squares). In both Experiments 5a and 5b, the number of elements in the line was 9 and the number of distractors was 50. The separation between squares in the line was equal to the side of a square and the smallest possible separation between distractors was .5 of the square separations in the line. In Experiment 5a, the combination of 2 square sizes, 3 square types, and 3 contrasts gave 12 stimuli. The squares were 12 and 24 pixels on a side. The squares were composed of 2x2 pixel checks, 4x4 pixel checks or were solid. The background luminance was set at 65.1 cd/m^2. The luminances of the checks were 0 and 130.2 cd/m^2. (contrasts of -1.0 and +1.0), and 41.5 and 88.7 cd/m^2. (contrasts of -.36 and +36). The luminances of the solid squares were set at 0 and 41.5 cd/m^2. (contrasts of -1.0 and -.36). It would



750
700
650
600
Reaction Time (msec)
8 Pixel Squares
16 Pixel Squares
0 2 8 16 24 32
Luminance (ft.-L.)
(1 pixel = 38 sec of arc)

(a)



3
2
1
0
Errors
8 Pixel Squares
16 Pixel Squares
0 2 8 16 24 32
Luminance (ft.-L.)
(1 pixel = 38 sec of arc)

(b)

Figure 10.

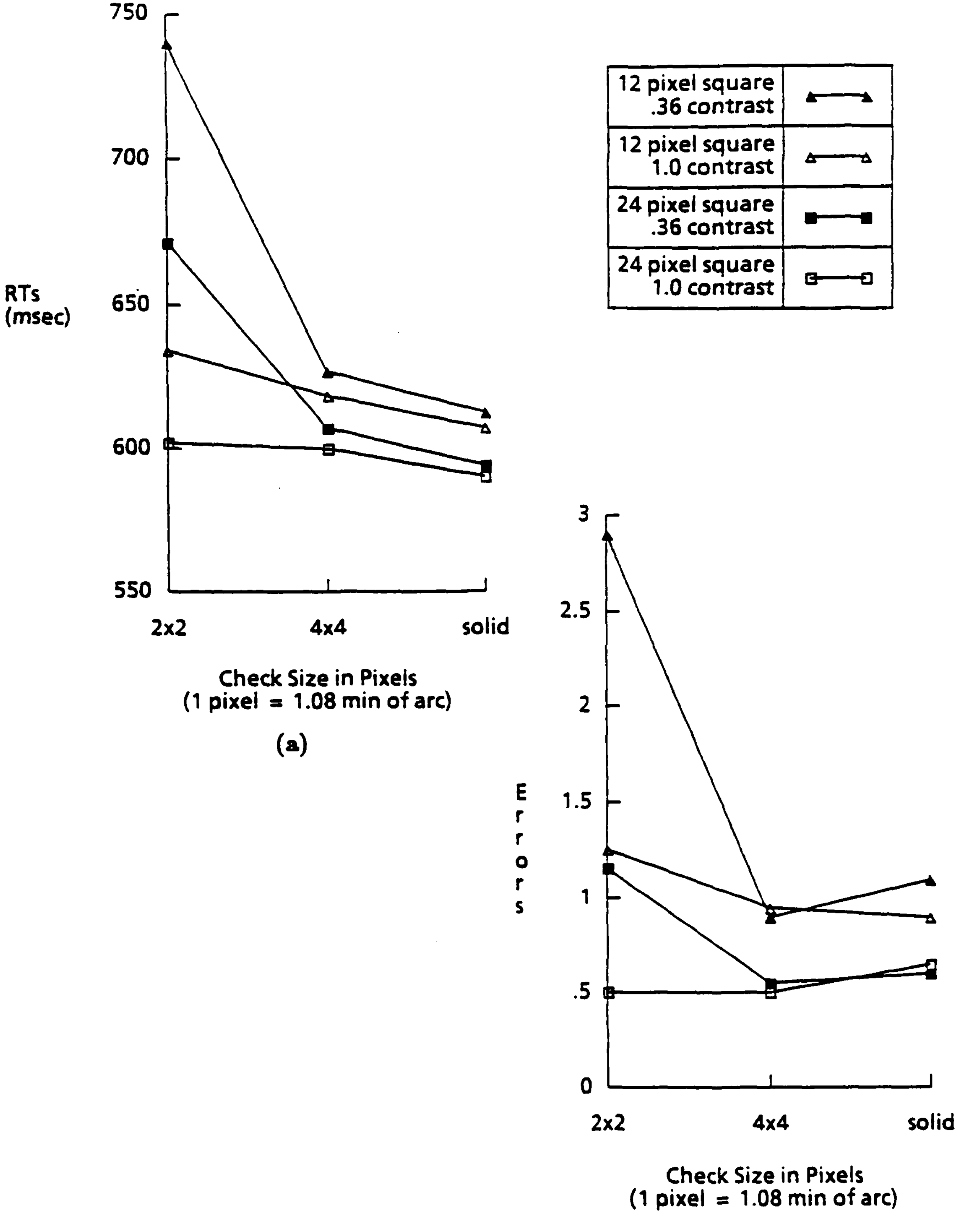

12 pixel square .36 contrast
12 pixel square 1.0 contrast
24 pixel square .36 contrast
24 pixel square 1.0 contrast
RTs (msec)
750
700
650
600
550
2x2
4x4
solid
Check Size in Pixels (1 pixel = 1.08 min of arc)
(a)
Errors
3
2.5
2
1.5
1
.5
0
2x2
4x4
solid
Check Size in Pixels (1 pixel = 1.08 min of arc)
(b)

Figure 11.

have been nice to show a figure of the Laplacian squares, but contrasts are changed greatly by publication. Figures 11a and 11b show the mean reaction times and mean total errors. The main effects of square size, contrast, square type, and the contrast by square type interaction were significant for both reaction times and errors. For the squares composed of 2x2 pixel checks, both reaction times and errors were markedly decreased by increased contrast and square size. For the solid squares and the squares composed of 4x4 pixel checks, square size and contrast affected reaction times and errors much less. There was little or no difference between the results for solid and Laplacian squares when the squares or checks had high contrast. This seems incompatible with a model based on density (i.e., on average luminance), since the luminances of the Laplacian squares average out to the luminance of the background.

In Experiment 5b, the Laplacian squares were composed of 2x2 pixel checks and were 12, 16, 20 and 24 pixels on a side. The background luminance was set at 65.1 cd/m^2. The luminances of the checks were 0 and 130.2 cd/m^2 (contrasts of -1.0 and +1.0), 23.0 and 107.2 cd/m^2 (contrasts of -.65 and +.65), and 45.6 cd/m^2 and 84.6 cd/m^2. (contrasts of -.30 and +.30). The mean reaction times and the mean total errors are shown in Figures 12a and 12b. The main effects of square size, contrast, and the square size by contrast interaction were significant for both reaction times and errors. There was a marked decrease in reaction time with increasing square size with a .30 contrast and smaller decreases with .65 and 1.0 contrasts. The error scores showed a decrease with increasing square size only with a .30 contrast. The results show that increasing the edge length of the Laplacian squares increased line segregation.

2.1.8 *Spatial Frequency Based Models*

Beck, Sutter, & Ivry (1987) investigated region segregation in periodic patterns composed of approximately equal numbers of two different elements. Perceived segregation depended on the difference in the arrangement of the elements. The elements were arranged in a striped pattern in the top and bottom regions and in a checked pattern in the center region. Figure 13 is an example of a display in which the two types of elements were large and small squares. They found region segregation to be a u-shaped function of the contrast ratio of the two squares.

The minimum occurred approximately at the point where the area x contrast of the large and small squares was equal. Sutter, Beck & Graham (1989) further investigated this trade-off between area and contrast. They showed that the dependence of perceived segregation on the areal contrasts of the elements was predictable from the degree to which the regions differentially activate spatial-frequency/orientation channels. A number of investigators have recently attempted to use differences in spatial frequency channel outputs to predict region segregation (Caelli, 1982, 1985; Daugman, 1987; Fogel & Sagi, 1989; Malik & Perona, 1989; Turner, 1986). It might be supposed that differences in the outputs of spatial frequency channels also determine perceived line segregation. In particular, differences in the outputs of channels in the line region and in neighboring regions above and below the line might control perceived line segregation. Our experimental results, however, indicate that this kind of computation does not account for the perceived segregation of the lines. The stronger segregation of lines composed of bars than of blobs (Experiment 1) and the similarity of the perceived segregation of lines composed of filled and outline squares (Experiment 3) suggest that the extent and alignment of edges is important in line segregation. The segregation of lines composed of Laplacians (Experiments 5a and 5b) also implicate edges as an important factor.

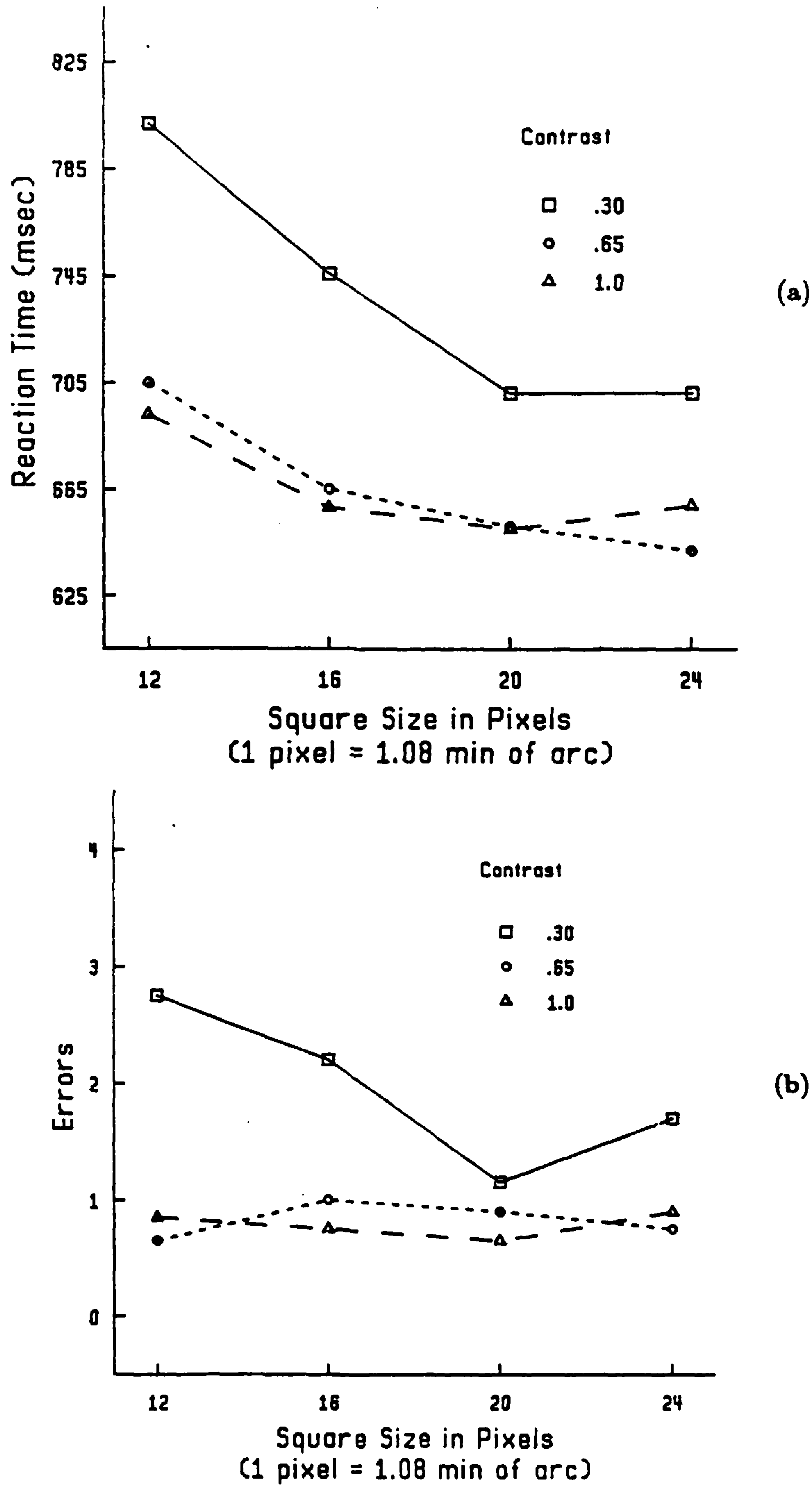

825
785
745
705
665
625
Reaction Time (msec)
Contrast
.30
.65
1.0
(a)
12
16
20
24
Square Size in Pixels
(1 pixel = 1.08 min of arc)
4
3
2
1
0
Errors
Contrast
.30
.65
1.0
(b)
12
16
20
24
Square Size in Pixels
(1 pixel = 1.08 min of arc)

Figure 12.

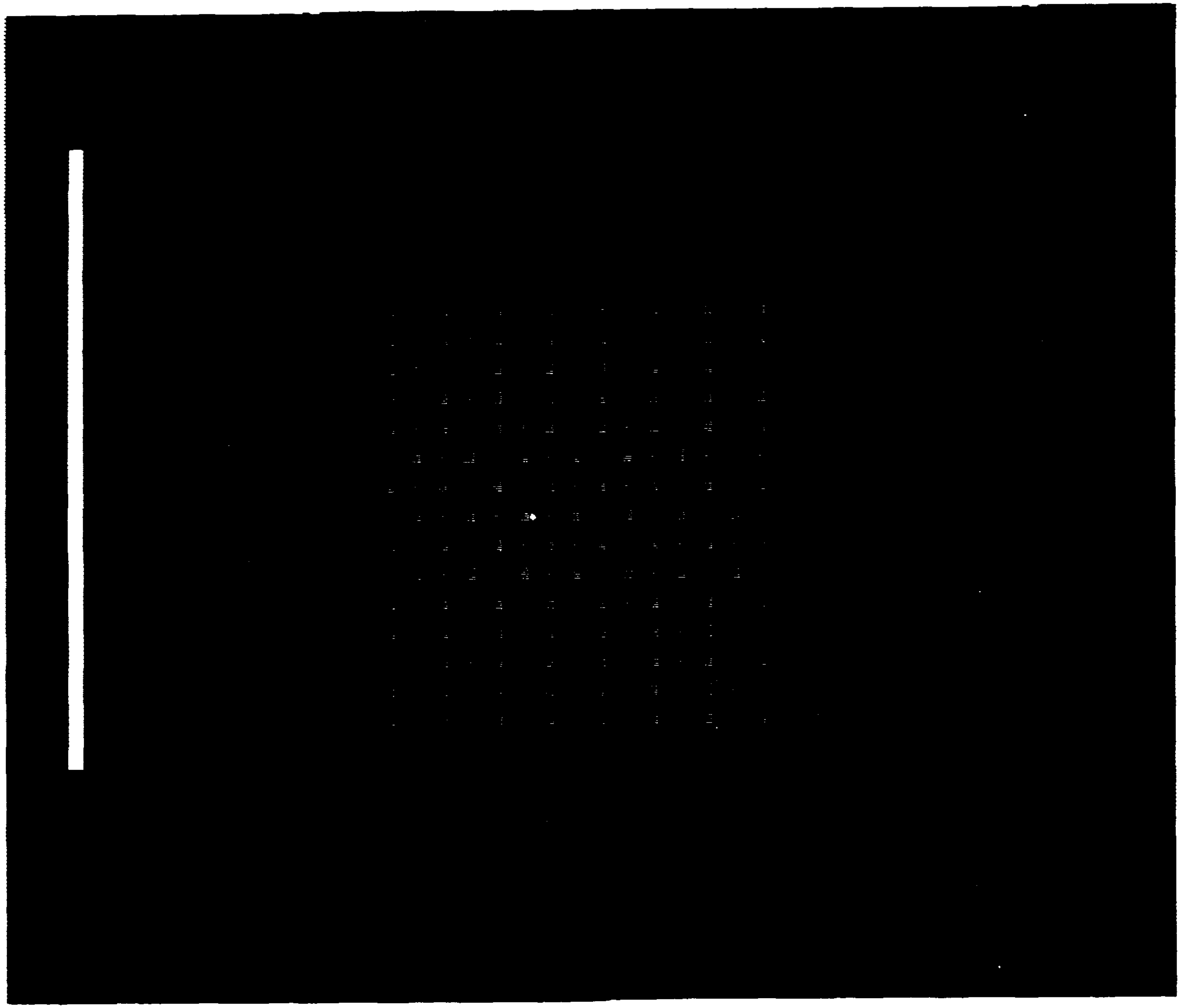


Figure 13

In order to further investigate whether spatial-frequency channel outputs are or are not consistent with the experimental results, we have examined whether the channel outputs in a strip centered on the line differ from the channel outputs in strips above and below the line.

We modeled the receptive-field weighting functions by two-dimensional Gabor functions after Daugman (1985) and Watson (1983). The spatial-frequency half-amplitude full-bandwith was one octave and the orientation half-amplitude full-bandwith was 38 degrees. We computed a spatially-pooled response of each channel to the middle strip and the top and bottom strips for different spatial-frequencies with a peak orientation of 90 degrees (horizontally). The maximum and/or standard deviation and mean of the channel outputs at different spatial positions within each strip were computed. For example, for computing the mean, the spatially pooled response of the i^{th} channel is

$$\underset{\text{in strip}}{R_i} = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \frac{O_i(x,y)}{N_x N_y} \qquad (1)$$

where N_x and N_y are the numbers of spatial positions in the x and y directions and O_i (x,y) is the output at position (x,y) of the channel tuned to the i^{th} frequency. The summing is done separately over the areas of the top, middle and bottom strips. We then computed the absolute difference between each filter's spatially-pooled response to the middle strip and to the top and bottom strips for the i^{th} filter

$$\text{Diff}_i = \left| \; 2\underset{\text{middle}}{R_i} - \underset{\text{top}}{R_i} - \underset{\text{bottom}}{R_i} \; \right| \qquad (2)$$

The variations in sensitivity with spatial frequency are not represented in Equation 1 but they were incorporated into the calculations of the model. The within filter differences across the different spatial-frequencies were weighted according to the observers' sensitivity to the different spatial-frequencies. In particular, the predicted value equals

$$\Delta = \sum_{i=1}^{N_f} \text{Diff}_i \, S_{\text{obs}}(f_i) \qquad (3)$$

where S_{obs} (f_i) is the sensitivity of the the observer to the i^{th} frequency and N_f is the number of frequencies. Analogous computations were carried out for the standard deviation and maximum of a channel's outputs. If Δ Values determined perceived line segregation, there should be a monotonic relationship between Δ Values and reaction times. It should be emphasized that the conclusions we report do not depend on our choice of contrast sensitivity function. The peak sensitivity was at 5.6 cycles/deg. The conclusions remain unchanged when the outputs were not weighted by the contrast sensitivity function.

We undertook three tests of the hypothesis that the segregation of the lines is predicted by differences in the weighted mean or standard deviation of a channel's output in a middle strip containing the line and neighboring strips above and below the line. We examined whether the perceived segregations of the lines composed of bars and blobs in Experiment 1 and of outline and filled squares in Experiment 3 are predicted by the Δ Values computed from the mean and standard deviation of a channel's outputs. In addition, we varied element shape, size, and contrast in an experiment specifically designed to test the hypothesis that perceived segregation is a function of differences in spatial-frequency channel outputs. We examined whether the Δ Values computed from the mean, standard deviation and maximum of a channel's outputs predict perceived line segregation.

In the analyses of Experiments 1 and 3, since the distractors were randomly generated, we filtered five randomly generated distractor patterns. The distribution of distractors was the same for the different conditions of an experiment. In Experiments 1 and 3, the number of frequencies was 7--from .5 to 32 cycles/deg in Experiment 1 and from .25 to 16 cycles/deg in Experiment 3. The frequencies increased by factors of 2. In Experiment 1, the collinear and orthogonal patterns composed of a bar and blob with a 1.8 aspect ratio were filtered. The height of the middle strip was 16 pixels for the collinear bar and blob patterns and 24 pixels for the orthogonal bar and blob patterns. The lengths of the strips in the collinear and orthogonal bar and blob patterns were 320 pixels. The heights of the top and bottom strips were 48 pixels. The means of the CSF-weighted differences of output means were 51.5 for the collinear bar and 49.0 for the collinear blob, and 25.1 for the orthogonal bar and 25.2 for the orthogonal blob. The means of the CSF-weighted differences of the output standard deviations were 26.1 and 24.0 for the collinear bar and blob and 15.9 and 15.7 for the orthogonal bar and blob. As expected, the means and standard deviations of the bar and blob outputs were highly similar and do not correspond to the perceived segregation of the line. The difference, for example, in the $\triangle$ Values of the collinear and orthogonal blobs is not reflected in the reaction time data (Figure 4a).

In Experiment 3, the patterns composed of lines with 10 pixel outline and solid squares separated by 10 pixels were filtered. The means of the CSF-weighted differences of output means were 15.6 for the outline squares and 25.7 for the solid squares. The means of the CSF-weighted differences of the output standard deviations were 13.1 and 17.4 for the outline and solid squares respectively. The differences in mean outputs for the outline squares differed significantly and were approximately 60% of those of the solid squares. However, the perceived segregations of the outline and solid squares did not differ significantly (Experiment 3).

2.1.9 *Experiment 6: Large Squares, Small Squares, and Rectangles*

We conducted a further experiment to investigate whether the perceived segregation of lines composed of large squares, small squares and rectangles is predicted by differences in the outputs of spatial frequency channels.

Stimuli and procedure. Stimulus patterns were composed of two elements which could be the same or could differ in size, shape or contrast. There were three types of figures: a 16 pixel square, an 8 pixel square, and a rectangle 16 pixels in height and 4 pixels in width (see Figure 14). The areas of the small square and rectangle were the same and the area of the large square was 4 times that of the small square and rectangle. The rectangles, as shown in Figure 14c, were orthogonal to the line. The patterns were presented on a gray (55.2 cd/m_2.) background. The luminances of the elements composing a pattern was set at either 62.1 cd/m_2 (a contrast of .125) or 82.8 cd/m_2 (a contrast of .5). The areal contrasts of the small square and rectangle were equal to that of the large square when their contrasts were .5 and the contrast of the large square was .125.

Twenty-one stimuli were presented. They represented the partial combination of the 3 figures and 2 contrast-ratios. They are listed in Table 1. The first column shows the two elements

TABLE 1

Mean Reaction Times and Standard Deviations in Experiment 6

Stimulus	1st Element (pixels)	2nd Element (pixels)	1st Element Contrast	2nd Element Contrast	Mean RT (msec)	SD (msec)
*1	8x8 sq	8x8 sq	.5	.5	740	101
2	8x8 sq	8x8 sq	.125	.5	782	115
*3	8x8 sq	8x8 sq	.125	.125	741	108
*4	16x16 sq	16x16 sq	.5	.5	725	76
5	16x16 sq	16x16 sq	.125	.5	746	100
*6	16x16 sq	16x16 sq	.125	.125	706	86
*7	4x16 rect	4x16 rect	.5	.5	774	101
*8	4x16 rect	4x16 rect	.125	.5	870	153
*9	4x16 rect	4x16 rect	.125	.125	824	125
10	16x16 sq	8x8 sq	.5	.5	736	91
*11	16x16 sq	8x8 sq	.125	.5	780	119
*12	16x16 sq	8x8 sq	.5	.125	792	129
13	16x16 sq	8x8 sq	.125	.125	759	125
14	16x16 sq	4x16 rect	.5	.5	737	94
*15	16x16 sq	4x16 rect	.125	.5	808	131
*16	16x16 sq	4x16 rect	.5	.125	796	130
17	16x16 sq	4x16 rect	.125	.125	787	150
18	4x16 rect	8x8 sq	.5	.5	794	103
19	4x16 rect	8x8 sq	.125	.5	872	167
20	4x16 rect	8x8 sq	.5	.125	843	129
21	4x16 rect	8x8 sq	.125	.125	820	145

sq = square; rect = rectangle; 1 pixel = 1.08 minutes; * = filtered composing a stimulus pattern, and the second the contrasts of the elements. One important difference from Experiments 1-5 is that the spatial positions of the distractors were not randomly generated for each stimulus presentation, but were kept constant. There were 52 distractors. There were 22 large squares and 30 small squares in patterns composed of large squares and small squares and 22 large squares and 30 rectangles in patterns composed of large squares and rectangles. When the patterns were composed of rectangles and small squares, there were 22 rectangles and 30 small squares. There were 8 elements in the line. A second difference is that the spatial separation of the elements in the line was center-to-center rather than contour-to-contour. The center-to-center separation of the elements was 40 pixels. When the line was composed of two different elements, the two elements alternated. The direction of the line was always horizontal. In half of the stimuli the line was in the top third of the display and in half in the bottom third of the display. The top and bottom positions of the line were fixed. The stimuli in which the line appeared in the bottom third were reflections across the midline of the stimuli in which the line appeared in the top third. Figure 14 shows the stimulus composed of (a) large squares, (b) small squares, and (c) rectangles with the line in the top region, and with the top, middle, and bottom, strips over which the statistics were computed outlined.

Except if noted otherwise, the procedure was the same as in Experiments 1-5. Subjects were instructed to depress the left response button if a horizontal line composed of pattern elements was in the upper half of a stimulus and to depress the right response button if the line was in the lower half of a stimulus. Subjects initiated each stimulus presentation by a key press. The stimuli were flashed for 1000 msec. The exposure duration was chosen to match the exposure duration in Sutter, Beck & Graham (1989). Subjects were told that the line could consist of elements having the same shape, size, and lightness, or different shapes, sizes, and lightnesses. In some cases the line would be easily seen while in others it would be more difficult. At the beginning of an experimental session, subjects were shown several stimuli with the line in the top of the display and with the line in the bottom of the display. Subjects were then given a practice block of trials. The practice block was followed by five experimental blocks of trials. In each block, each stimulus was presented twice, once in the upper half of the display and once in the lower half of the display. Thus, each subject made 10 responses to each stimulus. Reaction times and errors were recorded. The errors were few and were not analyzed. Sixteen subjects participated in the experiment.

Filtering of stimuli.--Eleven of the stimuli were filtered using frequencies from .25 to 4 cycles/deg that increased by the square root of 2. Higher frequencies were not used because their receptive fields fell only on single elements in the line. The outputs from higher frequencies would not be able to differentiate between the line elements and the distractors in the background. The stimuli are indicated by asterisks in Table 1. Statistics were computed for a middle strip 28 pixels in width and top and bottom strips 56 pixels in width. The lengths of the strips were 310 pixels. The absolute differences between the mean, standard deviation and maximum in the middle strip and those in the top and bottom strips were computed.

Results.--The third and fourth columns in Table 1 present the mean reaction times and standard deviations for each of the stimuli. Figure 15 plots the output differences (Δ Values) between the middle strip and the top and bottom strips for the mean, standard deviation, and

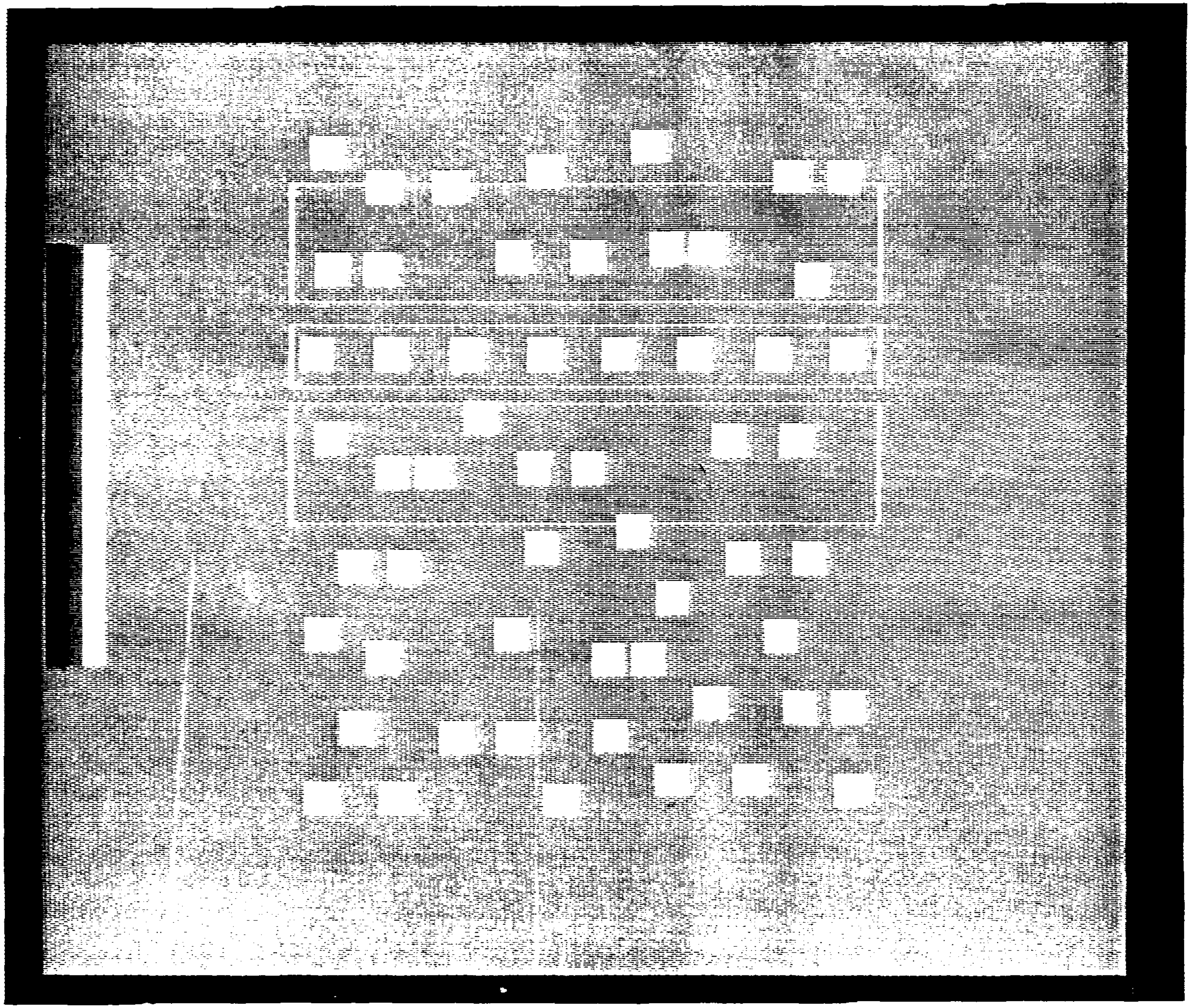


Figure 14 (a)

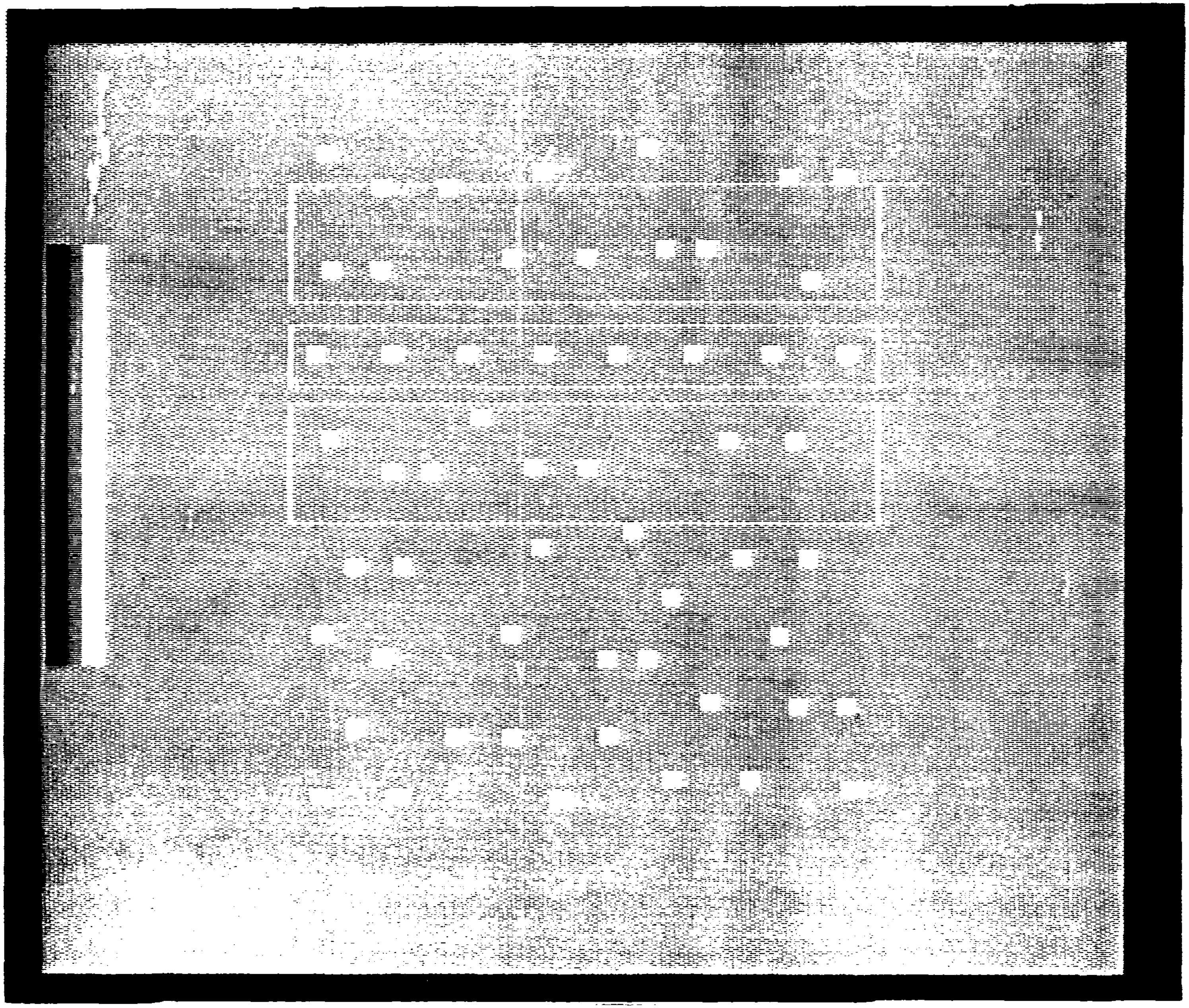


Figure 14 (b)

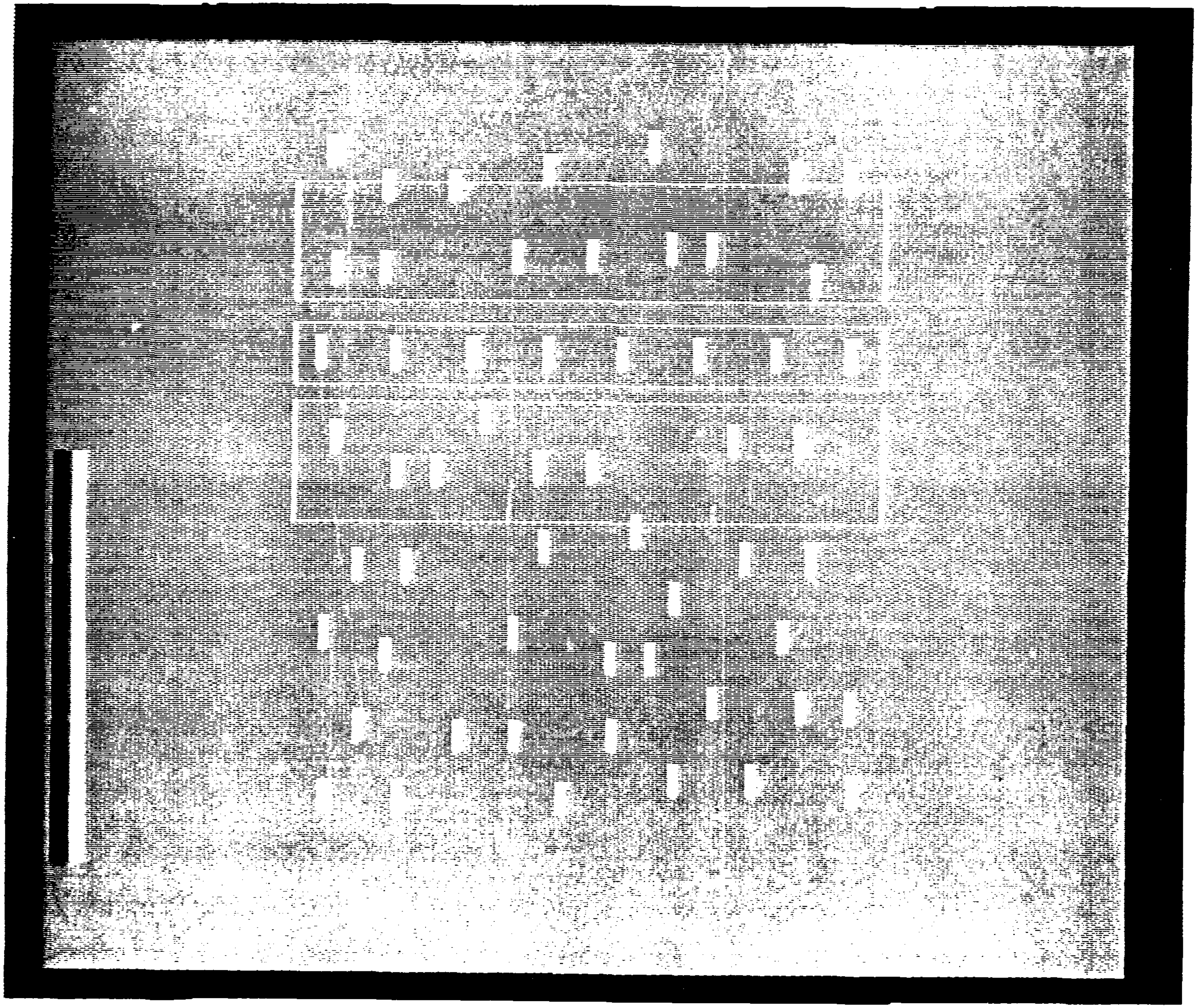
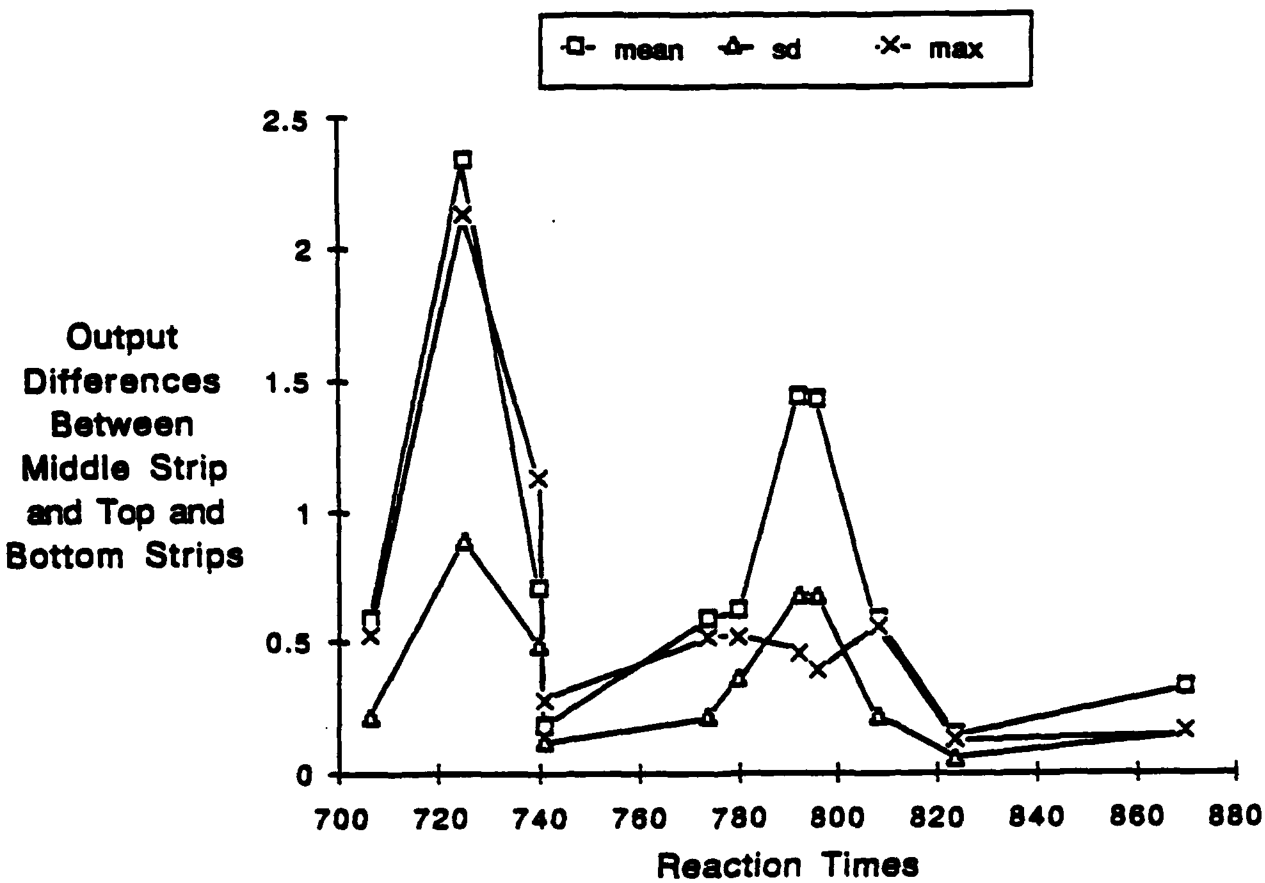


Figure 14 (c)



-□- mean -△- sd -×- max
Output Differences Between Middle Strip and Top and Bottom Strips
2.5
2
1.5
1
0.5
0
700 720 740 760 780 800 820 840 860 880
Reaction Times

Figure 15.

maximum as a function of subjects' mean reaction times. Reaction time is not a monotonic function of the output differences as would be expected if perceived segregation were determined by the outputs of spatial frequency channels. The peaks in Figure 15 are for stimuli 4, 12, and 16 in Table 2. We also computed statistics using top and bottom strip widths of 28 pixels. The pattern of results and conclusions are identical to those using top and bottom strip widths of 56 pixels.

An area x contrast tradeoff did not occur. The filtered outputs for the stimuli composed of two large squares with a contrast of .125 (Stimulus 6), two rectangles with a contrast of .5 (Stimulus 7), and a large square and a rectangle with contrasts of .125 and .5 respectively (Stimulus 15) were identical. The reaction times were 705 msec for Stimulus 6, 774 msec for Stimulus 7, and 808 msec for Stimulus 15. The reaction time for Stimulus 6 differed significantly from the reaction times for Stimuli 7 and 15. If segregation is a function of the weighted differences in the outputs of spatial-frequency channels, then the strength of segregation of the three targets should have been the same.

As would be expected, the reaction times for the patterns composed of two different elements were significantly greater than the reaction times for the patterns composed of a single element (two elements of the same shape and size.) For patterns composed of two identical elements, the size and shape of the elements significantly affected reaction times. Comparison across the three contrast conditions shows that the reaction times for the patterns composed of large squares were the least (725 msec for Stimulus 4, 746 msec for Stimulus 5, 706 msec for Stimulus 6), the reaction times for patterns composed of small squares were greater (740 msec for Stimulus 1, 781 msec for Stimulus 2, and 741 msec for Stimulus 3), and the reaction times for the patterns composed of rectangles were still greater (774 msec for Stimulus 7, 870 msec for Stimulus 8, and 824 msec for Stimulus 9). Examination of Table 1 shows that the segregation of the lines tended to be weakest when the rectangle was one of the elements of the pattern. The reaction times for patterns composed of the rectangle and small square were significantly greater than for patterns composed of the large square and small square. The reaction times for the patterns composed of the rectangle and small square were 794 msec (Stimulus 18), 872 msec (Stimulus 19), 843 msec (Stimulus 20) and 820 (Stimulus 21). The reaction times for the patterns composed of the large and small squares were 736 msec (Stimulus 10), 780 msec (Stimulus 11), 792 msec (Stimulus 12), and 759 msec (Stimulus 13). The results are consistent with the finding in Experiment 1 that a line composed of rectangles orthogonal to the direction of the line gives less strong segregation.

The contrast factor was also significant both for patterns composed of two identical elements and for patterns composed of two different elements. The fastest reaction times were for patterns composed of elements with a contrast of .5, slower for the patterns composed of elements with a contrast of .125 and slowest for the patterns composed of elements of differing contrast.

2.1.10 *Region Segregation and Line Segregation.*

Why do spatial frequency channel outputs predict texture segregation in the patterns studied by Sutter, Beck & Graham (1989), but fail to predict line segregation? Our results differ from those obtained with the periodic patterns they studied in two ways. First, an area x contrast tradeoff occurred in the tripartite patterns, but not in the line segregation patterns. It should be noted that the tradeoff between area and contrast in the tripartite patterns was not perfect. There were two nonlinearities (Graham, Beck & Sutter, 1989). There was an intensity dependent stimulus compression that may be due to light adaptation or intracortical interactions (Grossberg & Mingolla, 1985; Malik & Perona, 1989). The second nonlinearity is a rectification nonlinearity. Graham, Beck, & Sutter (1989) proposed a more complicated spatial-frequency channels model in which each channel contains in addition to an initial linear filtering, a nonlinear rectification followed by a second linear filtering. Linear filtering followed by a rectifying nonlinearity has been suggested by others such as Grossberg & Mingolla (1985), Chubb & Sperling (1988), Bergen and Adelson (1988), Malik & Perona (1989), and Fogel & Sagi (1989).

Second, unlike in the line displays, perceived segregation in their patterns was not affected by the misalignment of edges. Judgments of perceived segregation were indistinguishable when the elements in Figure 13 were aligned squares, misaligned squares, circles, or blobs (Poulson, 1988). What is the difference between their texture patterns and the line segregation patterns?

The small bar detectors, spot detectors, and edge detectors provide no information for segregating the regions in the display shown in Figure 13. These detectors indicate that there are two populations--large and small squares. There is, however, no spatial differentiation as a result of their outputs. The centroids of the populations of large and small squares are the same. There is also no information from the edge detectors. Although there is more alignment of the squares in the top and bottom (striped) regions than in the center (checked) region, alignment is present in all regions. The greater degree of alignment in the striped regions, however, is not sufficient to give strong segregation. The detectors showing strikingly different outputs to the different arrangement of elements in the striped and checked regions are at the fundamental periods of the pattern. They respond to the periodicity of the pattern and signal the differences in the overall pattern of luminance changes in the striped and checked regions. In the striped region the changes in overall luminance occur in the direction of the X axis, and in the checked region, in a direction 45 degrees from the X axis. An area x contrast tradeoff occurs because the channels in which the differential activation to the striped and checked regions is greatest are those sensitive to the fundamental frequencies and orientations of the patterns. Since the outputs from the higher spatial frequency channels have very little effect on perceived segregation, and since channels tuned to the higher frequencies respond to the edges of the elements in a pattern, altering the contours of the elements also has little effect on perceived segregation.

In the line displays, the line consists of elements having the same size, contrast, and orientation as the distractor elements. The small bar detectors and edge detectors give similar responses to elements in the line and to the distractors. Line segregation can also not be explained in terms of differences in the responses of large bar detectors. In modeling of simple cells by 2D Gabor functions, the bar detectors become wider as they become longer. A detector long enough to fall on three elements of the line will also fall on many distractor elements. Strongly oriented receptive fields with large major to minor axis ratios are rare (De Valois, Yund, & Helper, 1982; De Valois, Albrecht, & Thorell, 1982). What is suggested is that line segregation is not the direct result of differences in the outputs of large bar detectors, but rather results from the further processing of the outputs of small bar, spot and edge detectors.

What other types of models might account for line segregation? We have shown that it is unlikely to be due to the direct detection of the lines by large bar detectors. The experiments with Laplacian squares show that line segregation may occur even if the line cannot be detected by large bar detectors. Analogously, global structure may be detected in patterns which have been filtered so that no low spatial-frequencies are present (Janez, 1984). Prazdny (1986) has shown that global structures can be seen in random dot Glass patterns that do not contain spatial frequency information corresponding to their structures.

What kind of processes might operate on the outputs of low-level visual analyzers to give line segregation? We shall discuss three possibilities.

2.1.11 *Other Types of Models*

Element grouping.--The first possibility is that the line is detected by a process involving an explicit grouping of the line elements. Our experiments show that edges are an important factor. The linking together of collinear edges as a way of detecting global structure was proposed by Beck (1982, 1983) and Beck, Prazdny & Rosenfeld (1983). Grossberg (Grossberg & Mingolla, 1985; Grossberg, 1987) has proposed a specific model of how the visual system creates "invisible" boundaries from edge pieces. These invisible boundaries become the basis for perceiving global line structures. The computational model proposed by Sha'ashua & Ullman (1988) for the salience of curves can be interpreted in terms of a mechanism that groups edge elements so as to maximize curve simplicity. Zucker (1983) has also proposed a computational model for grouping edge elements.

Our experimental results also indicate that line segregation is a function of edge grouping. Segregation decreased with edge misalignment and edge irregularity and increased with the amount of edge present. The similarity of the results for outline and solid squares and the increased segregation of Laplacian squares with their size also prove that edges are the important factor. Possible edge detectors are receptive fields with odd symmetry found by Hubel and Wiesel (1962, 1968) in cat and monkey. The outputs of edge detectors are oriented edge elements that may group to form a long line. The length of the line is an emergent feature that makes it stand out from the surrounding region.

The role of grouping in segregation has also been shown by Enns (1988). Enns showed that "popout" occurs not only for two-dimensional features but also for differences in orientation resulting from the three-dimensional interpretation of the features. Grouping processes are strongly implicated in an important series of experiments on Glass patterns by Prazdny (1986), who has shown that geometric properties are important using competing Glass pattern displays (radial vs concentric organizations). Two kinds of grouping processes appear to be involved in Glass patterns. The first is the grouping of pairs of elements on the basis of proximity. Pair grouping is an inverse function of element size difference and of element separation. Second, there is a grouping of the pairs of elements based on the slopes defined by the element pairs. For example, in Figure 2 of Prazdny (1986), the spiral Glass pattern disappears when the separations between the large and small dots are made large because the tendency to group the large dots with the small dots (pair grouping) fails to occur. There is a competition between grouping small dots with small dots and small dots with large dots. When the small dots are closer to the large dots, they group with the large dots and the spiral pattern is visible. Pair grouping is increased by increasing the size of the small dots and by increasing interpair distance. Scaling of this demonstration shows that the relative spacing is what is important.

Feature density.--A second possibility is that line segregation is based on the spatial density of specific features. One may think of sliding a long, narrow, horizontal window over one of our stimulus patterns, and counting the number of elements of particular types lying within the window. It is possible that there exists a detector that "heats up" when it is stimulated more by particular features. Such detectors operate on the outputs of low-level visual analyzers. Beck, Prazdny & Rosenfeld (1983) proposed that preattentive texture segregation depends on differences in the first order statistics of specific features. Julesz (1984) proposed that preattentive perception is mediated by the detection of density differences of features he called textons. Textons include elongated blobs, terminators, and crossings. Our arguments in Section 2 against density as a basis for line segregation apply only to pixel density, not to feature or texton density. Fogel & Sagi (1989) reported that Gabor filters predict texton based texture segregation except for terminators. Taylor & Badcock (1988) have shown that the visual system is more sensitive to the presence or absence of terminators than to differences in their density.

Search.--A third possibility is that line segregation is the result of a fast search process. Local features may attract attention. The detectors of properties such as the collinearity of edges may initiate a search process for objects having the same properties in the neighboring region. The search is focused by straight edges. Short edges would not be expected to focus search as well as long edges. For misaligned elements the focusing does not help. Rapid line segregation occurs because local features focus the search in a given direction. The fact that lines composed of bars perpendicular to the line in Experiments 1 and 6 were less salient than lines composed of bars parallel to the line is consistent with a hypothesized search process. Element orientations perpendicular to the direction of the line interfere with searching in the direction of the line.

An argument against a search-based explanation of line segregation is that search is inherently sequential, hence may be too slow to account for the speed of the segregation process. Searching for a line in a strip n elements long may require on the order of n computational steps, in which n is several hundred. However, it has been found that parallel processing techniques using an exponentially tapering "pyramid" of processing elements can greatly speed up the search process so that it requires only on the order of $\log_2 n$ computational steps. Pyramid algorithms can also be used to model other types of segregation processes involving subpopulations, regions, or isolated features. A review of pyramid models for perceptual grouping processes can be found in Rosenfeld, (1986).

2.2 Effects of Lightness Differences on the Perceived Segregation of Regions and Populations

Four experiments investigated the relation of perceived segregation to lightness differences. d od of this report. The subjects both rated the perceived segregation of a stimulus and matched the lightnesses of the light and dark squares in a pattern to a lightness scale. The experiments compared the perceived segregation of a pattern into regions and into subpopulations. In Experiments 1 and 2, the light and dark squares were arranged in 15 rows and 15 columns (Figure 16). The subjects rated the perceived segregation of a stimulus into three regions. In Experiments 3 and 4, the light and dark squares were randomly distributed throughout the pattern (Figures.17a and 17b). The subjects rated the perceived segregation of a stimulus into two subpopulations. Experiments 2, 3 and 4 were conducted during the period of this report. Experiment 1 was conducted prior to the report period. The four experiments are presently being written up for publication and Experiement 1 has been included for completeness.

2.2.1 *Introduction*

Beck, Sutter, & Ivry (1987) investigated region segregation in three-part patterns in which each part contained approximately equal numbers of two different elements on a background of

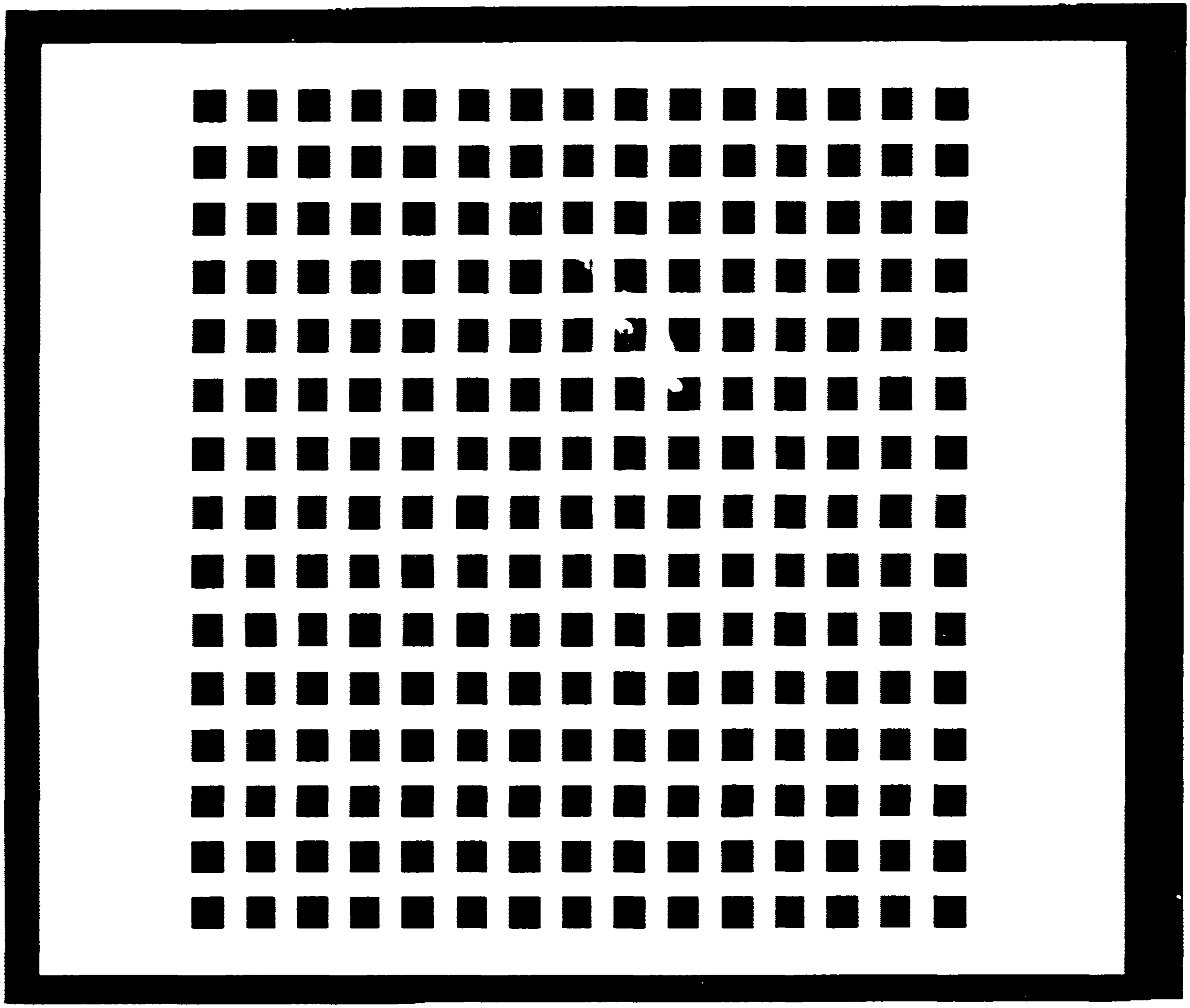


Figure 16

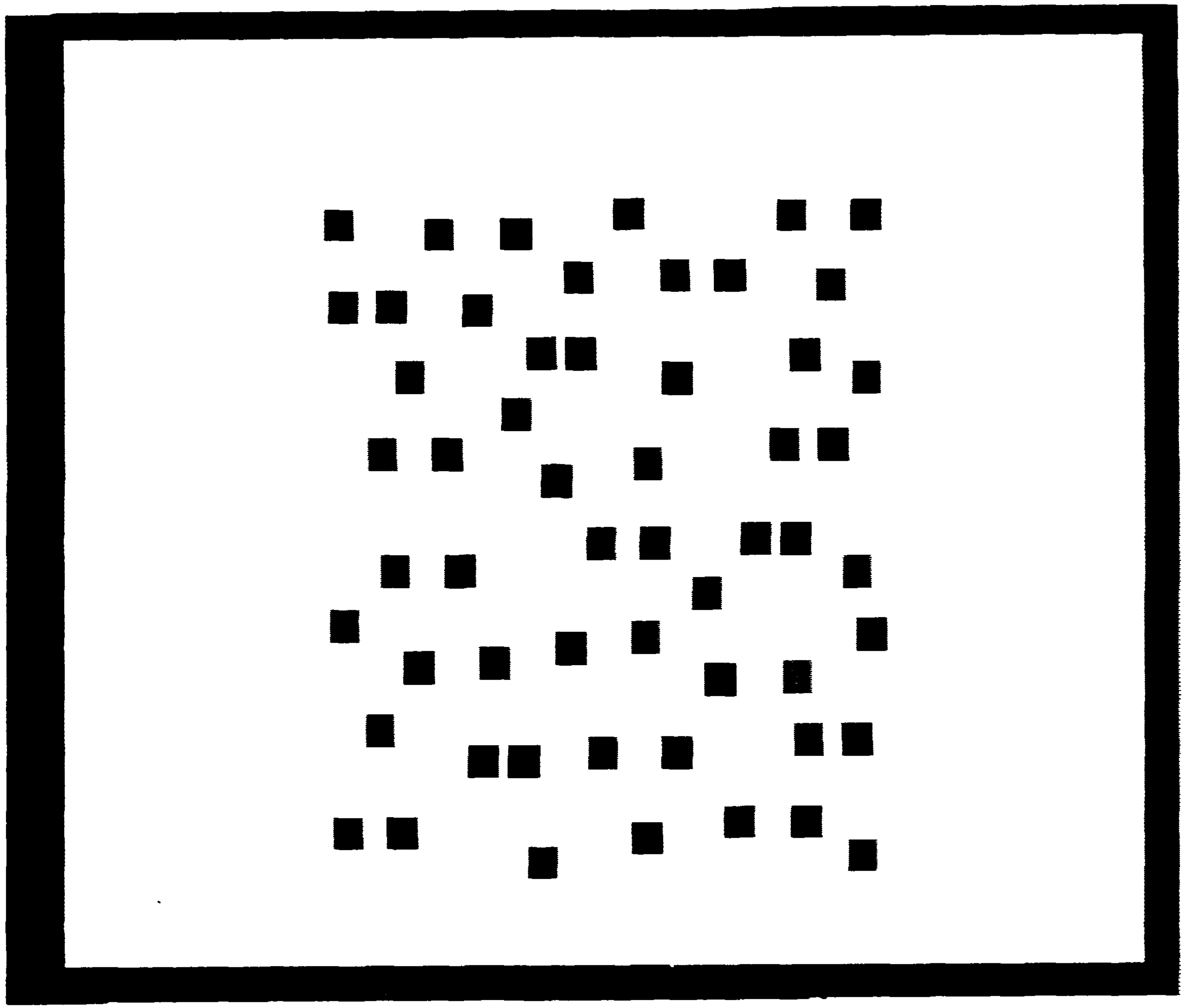


Figure 17 (a)

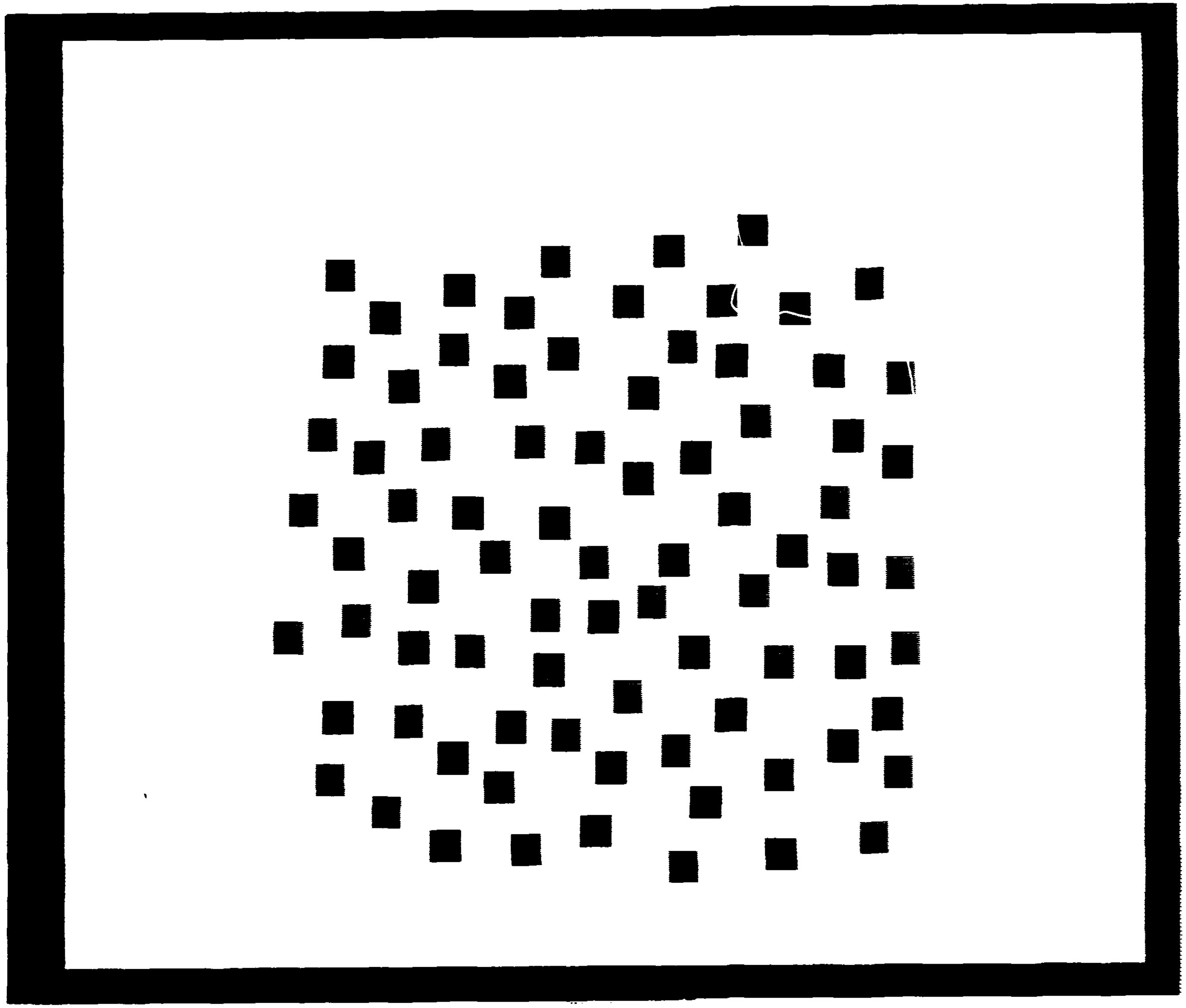


Figure 17 (b)

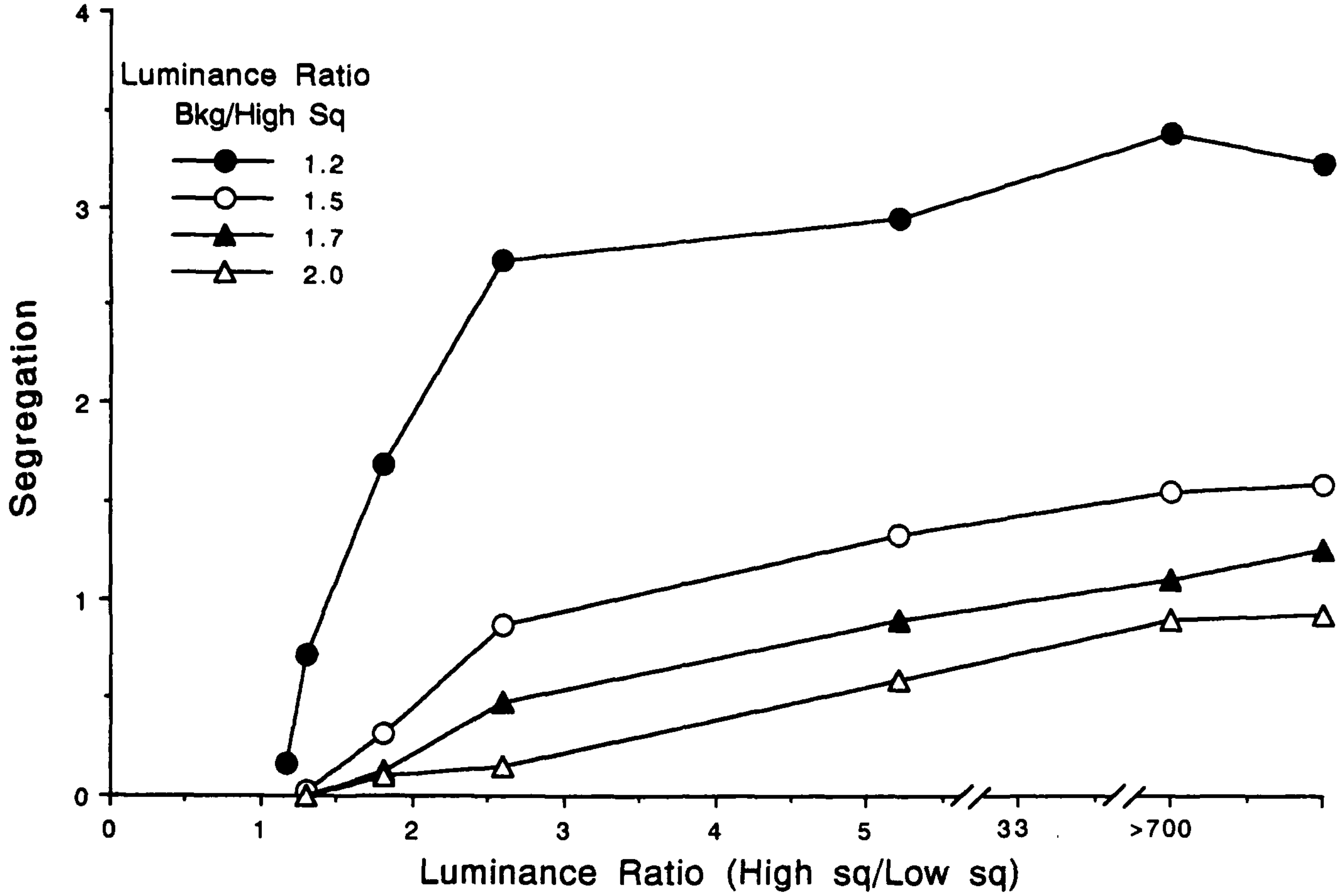
uniform luminance (e.g., light and dark squares on a white background in Figures 16). The regions to be segregated differed in the arrangement of the squares. In the top and bottom regions, the squares were arranged in vertical stripes. In the center region, the squares were arranged in a checked pattern. A striking observation reported by Beck, Sutter, & Ivry (1987) was that squares differing by a large lightness difference sometimes failed to give region segregation, while the same pattern of squares differing by a smaller lightness difference yielded strong region segregation. (It would have been nice to include figures that demonstrate this but the lightness values are distorted by the photocopying process.) In the experiment reported by Beck, Sutter & Ivry (1987), the lightness judgments were made informally by the experimenters. However, perceived region segregation plotted as a function of the ratio of the luminances of the light to dark squares suggested that the strength of region segregation is not a single-valued function of the lightness difference between the squares. When the luminance of a background is greater than the luminance of a surface, the lightness of the surface is determined by the ratio of the surface luminance to the average luminance of its background (Helson, 1964; Flock, 1970, 1972; Flock & Noguchi, 1970; Gilchrist & Jacobson, 1989; Jacobson & Gilchrist, 1988; Heinemann, 1989). Lightness is also generally agreed to be to a first approximation a logarithmic function of the relative luminance of the surface to its background (Judd & Wyszecki, 1963). From these two assumptions, and the background luminance the same, the difference in lightness of the light and dark squares is given by the equation:

$$Y_1 - Y_2 = k \log L_1/L_2 \tag{1}$$

where Y_i is lightness and L_i is the luminance of a square. In Figures 18a and 18b, we replot the data from Beck, Sutter & Ivry (1987). The squares were on a white (high luminance) background. Figure 18a plots perceived region segregation as a function of the ratio of the luminances of the light and dark squares. Perceived region segregation is not a single-valued function of the ratio of their luminances. For example, when the background luminance to that of the light square was 1.2, perceived segregation improved greatly with increasing luminance ratios of the light to dark squares (filled circles). When the ratio of the background luminance to the luminance of the light square was 2.0, perceived segregation was poor even when the luminance ratio of the light to dark squares was very large (open triangles). Since it is the ratio of the luminances of the light to dark squares that to a first approximation determines their lightness difference, the diverse curves in Figure 19a suggests that region segregation is not a simple function of the lightness difference between the squares. Figure 18b plots perceived region segregation as a function of the ratio of the dark (high contrast) and light (low contrast) squares. When plotted as a function of the ratio of their contrasts, perceived region segregation is a monotonic negatively accelerated single-valued function.

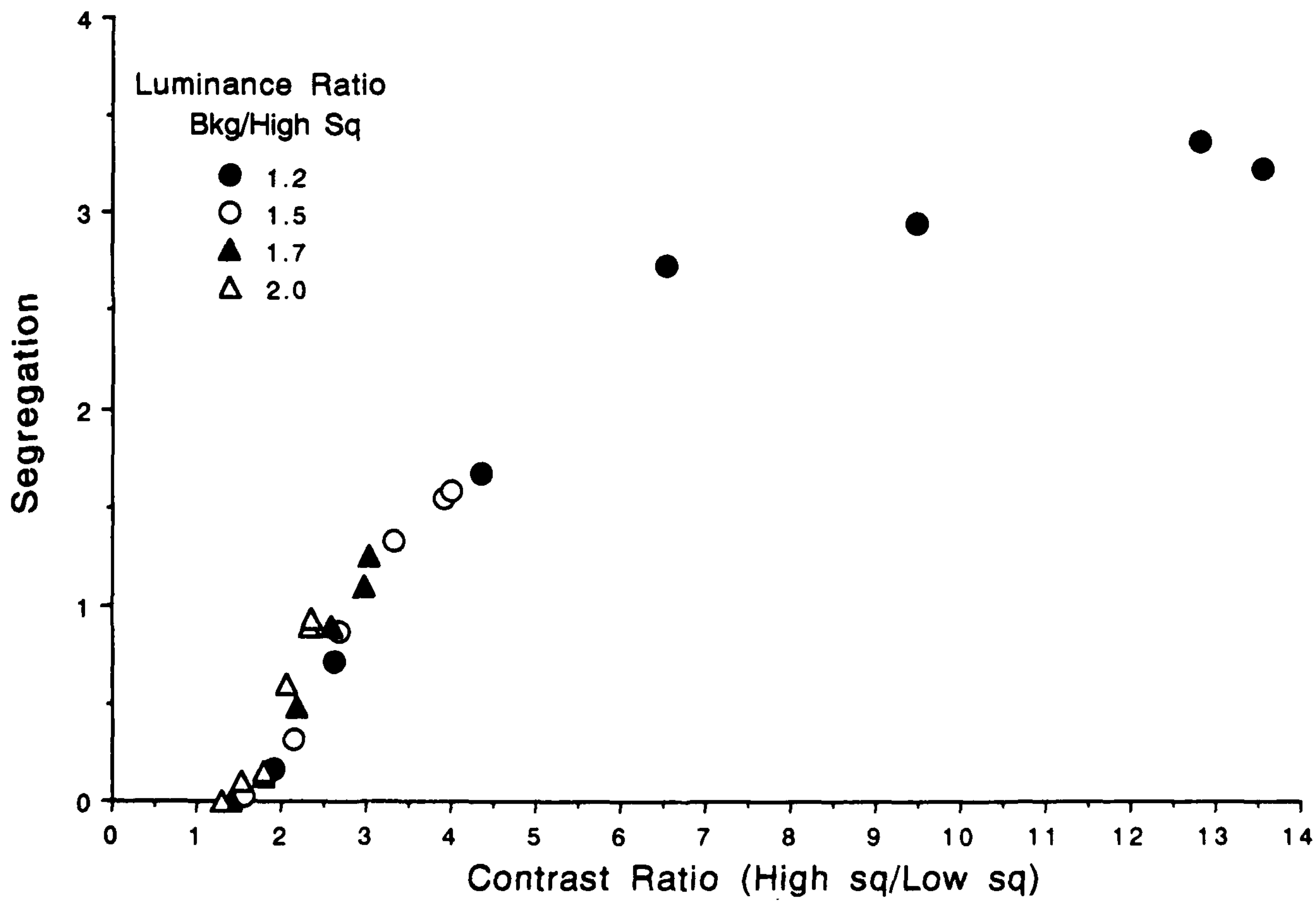
2.2.2 *Method*

Stimuli and Apparatus.--The stimuli were generated by a Symbolics 3600 Lisp machine. In Experiment 1, the stimuli were pictures of the computer generated images printed on a Tektronix 4634 hardcopy unit. In Experiments 2, 3, and 4, the stimuli were presented on a Tektronix 690 SR RGB monitor. Subjects viewed the stimuli from a distance of 3.5 ft. in Experiment 1 and from a distance of 6 ft. in Experiments 2, 3, and 4. The squares were .2 in. on a side in Experiment 1 and .36 in. (16 pixels) on a side in Experiment 2. A square subtended 16 min of arc in Experiment 1 and 17.28 min of arc in Experiments 2, 3, and 4 (1 pixel = 1.08 min on the RGB monitor). The center-to-center distances of the squares were .26 in. in Experiment 1 and .63 in. (28 pixels) in



Luminance Ratio
Bkg/High Sq
1.2
1.5
1.7
2.0
Segregation
0
1
2
3
4
0
1
2
3
4
5
33
>700
Luminance Ratio (High sq/Low sq)

(a)



Luminance Ratio
Bkg/High Sq
1.2
1.5
1.7
2.0
Segregation
0
1
2
3
4
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Contrast Ratio (High sq/Low sq)

Figure 18

(b)

Experiments 2. In Experiments 3 and 4, the squares were randomly distributed throughout the pattern and the center-to-center distances of the squares varied. Luminances were measured with a Spectra-Pritchard spot meter.

Segregation Ratings.--In all four experiments, the subjects made three ratings of each of the stimuli in an experiment. The stimuli were presented, in a random order in three blocks of trials. In Experiments 1 and 2, the subjects were asked to rate on a 5-point scale from 0 to 4 the distinctness of the three regions in a pattern. They were instructed not to scrutinize the patterns to find the boundaries between the three regions, but rather to base their judgments on their first impressions. In Experiments 3 and 4, they were asked to rate the segregation of the two intermixed populations on a scale from 0 to 4. A rating of 4 indicated that the regions in a pattern in Experiments 1 and 2 or the subpopulations in Experiments 3 and 4 segregated strongly. A rating of 0 indicated that the regions or subpopulations in a pattern did not segregate at all, i.e., they appeared to constitute a single pattern. In all four experiments, the subjects were shown sample stimuli to familiarize them with the range of stimulus variations.

In Experiment 1, the stimuli were placed by the experimenter on a stand. The exposure duration was not controlled. A stimulus was removed as soon as a subject made his judgment. Subjects made their judgments readily and quickly. In Experiments 2, 3, and 4, the subjects initiated each experimental trial by pushing a mouse button situated on a desk in front of them. An experimental trial consisted of the following sequence: a blue fixation X was presented for one second in the center of a blank screen; immediately after the offset of the fixation X, the stimulus appeared and remained on the screen for one second, after which it disappeared and the screen was blank. Throughout an experiment, including intervals during which the screen was blank, the background luminance of the screen remained constant at the value of the background for the stimuli in that experiment. After the stimulus disappeared from the screen, the subjects recorded their rating on a rating sheet and pushed the mouse button to initiate the next trial.

Lightness Matches.--After the three segregation ratings were completed, subjects made two matches of the lightnesses of the light and dark squares in a pattern. The stimuli were presented, in a random order, in two blocks of trials. The subjects were asked to match the lightness of the two squares in a pattern to a gray scale. In Experiment 1, the gray scale was 32-step Munsell chart ranging from a Munsell Value of 9.5 to a Munsell Value of 1.75 in .25 steps. The chart was held in a subject's hand. In Experiments 2, 3, and 4, the scale appeared on the CRT to the right of the texture pattern. It contained 10 gray levels that ranged from white to black. The gray scale was numbered from 1 to 10 and appeared against a gray background (9.96 fL). The luminances of the comparison rectangles were 0, .7, 1.56, 2.64, 6.06, 8.22, 9.96, 14.4, 20.25, 31.6 fL. The mean Munsell matches made by three observers of these luminances using a 10-step Munsell scale ranging from a Munsell Value of 9.5 to a Munsell value of 1.0 in 1.0 steps were Munsell Values of: 1.75, 2.75, 3.75, 4.58, 6.33, 7.50, 8.17, 8.75, 9.0, and 9.50. The gray scale was displaced by approximately 2 degrees (110 pixels) from the right edge of a stimulus pattern.

The subjects were encouraged to use decimal values if the lightness of a square appeared to lie between two gray scale values. Subjects could look alternately at a stimulus pattern and the gray scale comparison chart. Depressing the left mouse button displayed a stimulus, and depressing the right mouse button displayed the comparison lightness chart. Subjects recorded their lightness matches on a rating sheet and depressed the middle mouse button to initiate the next trial. In all four experiments, subjects were given as much time as they needed to match the lightnesses of the squares to the gray values on the comparison chart. The lightness difference between the light and dark squares composing a stimulus were computed from the mean lightness matches made by subjects of the light and dark squares.

Subjects.--Ten subjects served in each experiment. All subjects had normal or corrected-to-normal vision, and were paid for their participation.

2.2.3 *Experiment 1: Region Segregation--White Background*

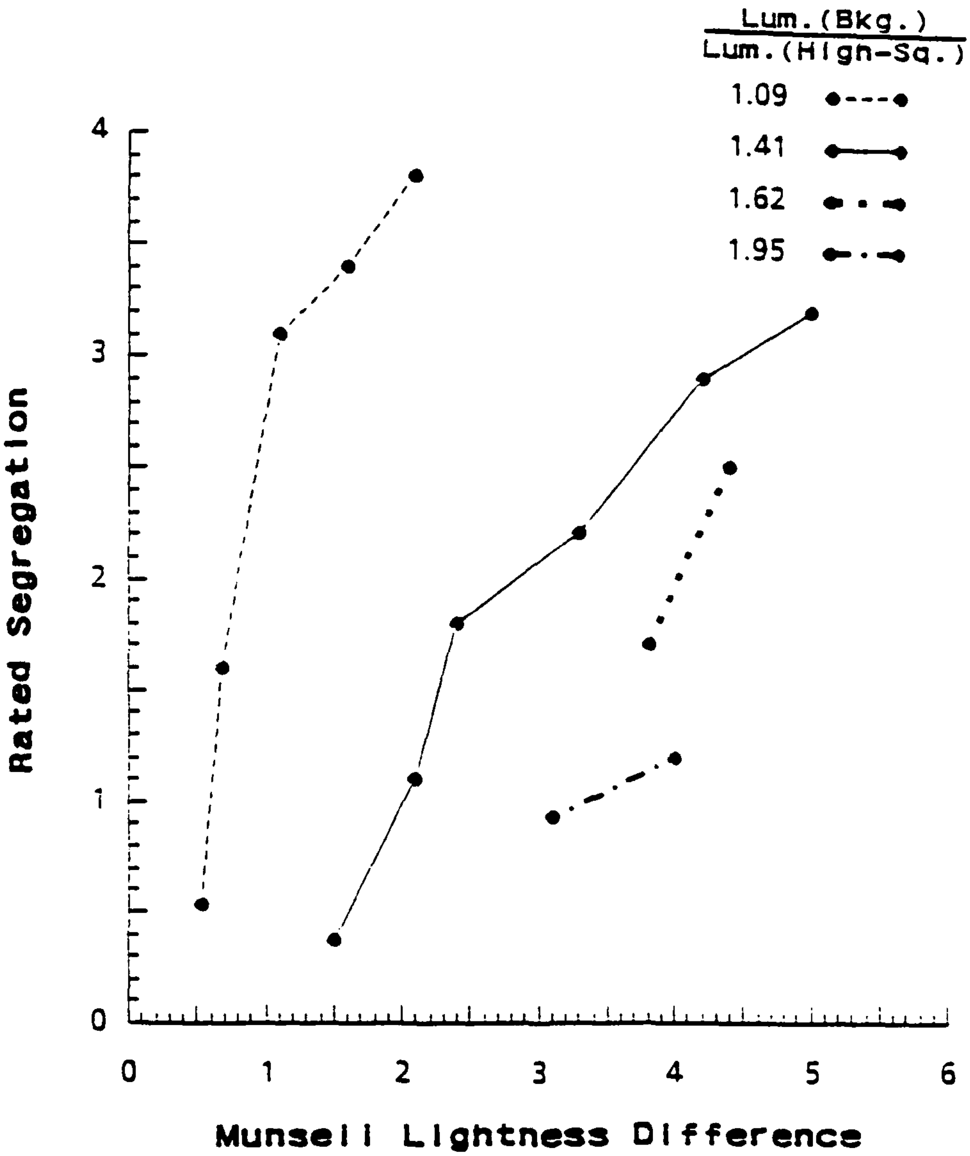
The aim of Experiment 1 was to investigate whether region segregation in the tripartite pattern is a single-valued function of the lightness differences or of the contrast ratios of the light and dark squares. The light and dark squares were on a white (higher luminance) background.

Stimuli.--Fifteen stimuli were presented. The background luminance was 38 ft.-L. For five stimuli, the light square was 35 ft.-L. and the dark square was 32, 31, 27, 23.5 or 19.5 ft.-L. respectively. For the six stimuli, the light square was 27 ft.-L. and the dark square was 19.5, 15.5, 11.5, 10, 6, or 3.5 ft.-L. respectively. For two stimuli, the light square was 23.5 ft.-L. and the dark square was 6 and 3.5 ft.-L. respectively. For two stimuli, the light square was 19.5 ft.-L. and the dark square was 6 and 3 ft.-L. respectively.

Region Segregation.--Figure 19 shows perceived region segregation as a function of the lightness difference calculated from subjects lightness matches of the light and dark squares. There is no simple functional relationship between perceived region segregation and the magnitude of the lightness difference. As in Beck, Sutter, & Ivry (1987), equal lightness difference lead to different perceived region segregation depending on the relationship of the background luminance to the luminance of the light square. For example, when the ratio of the background luminance to the luminance of the light square was 1.09, good region segregation occurred with Munsell lightness differences of between 1 and 2 steps. When the ratio of the background luminance to the luminance of the light square was 1.95, region segregation failed to occur with Munsell lightness differences of 3 and 4 steps.

Perceived region segregation plotted as a function of the ratio of the luminances of the light and dark squares is shown in Figure 20a. Perceived segregation is not a single-valued function of the luminance ratios of the light and dark squares. When the ratio of the background luminance to the luminance of the light square was 1.09, perceived region segregation increased dramatically as a function of the luminance ratio of the light and dark squares. When the ratio of the luminance of the background to the light square was 1.95, perceived region segregation remained weak with much larger luminance ratios of the light and dark squares. Perceived segregation as a function of the ratio of the contrasts of the light and dark squares is shown in Figure 20b. Perceived region segregation is a single-valued function of the ratio of the contrasts of the light and dark squares. In Figure 20b the results all fell on the same function within experimental error and so are not distinguished.

Lightness Differences.--The differences between subjects' lightness matches of the light and dark squares plotted as a function of the ratio of their luminances is shown in Figure 20c and as a function of the ratio of the their contrasts in Figure 20d. Lightness differences are a single-valued function of the ratio of the luminances of the light and dark squares (Figure 20c) but



Lum.(Bkg.)
Lum.(High-Sq.)
1.09
1.41
1.62
1.95
Rated Segregation
0
1
2
3
4
0
1
2
3
4
5
6
Munsell Lightness Difference

Figure 19

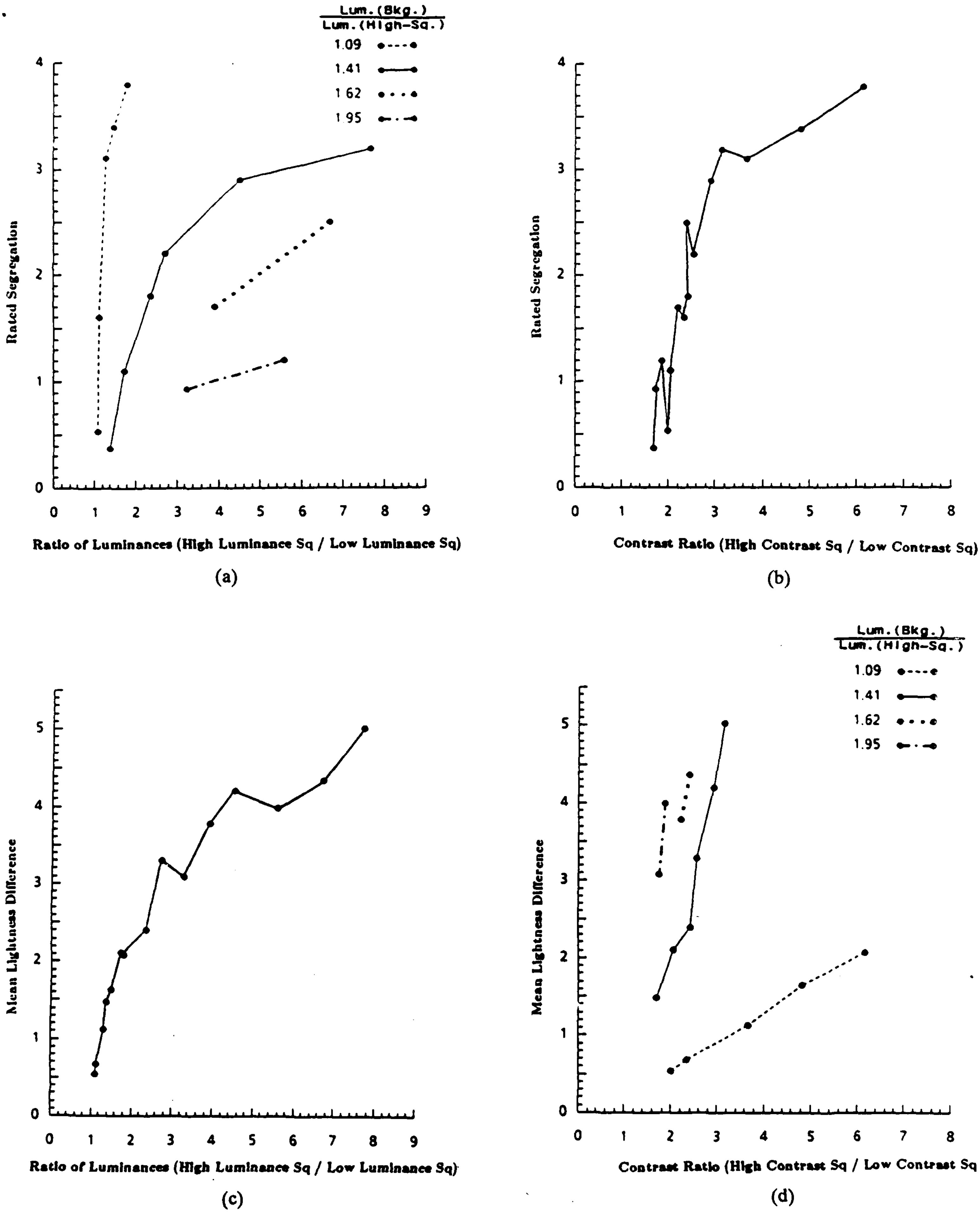

Lum.(Bkg.) / Lum.(High-Sq.)
1.09
1.41
1.62
1.95
Rated Segregation
Ratio of Luminances (High Luminance Sq / Low Luminance Sq)
(a)
Rated Segregation
Contrast Ratio (High Contrast Sq / Low Contrast Sq)
(b)
Mean Lightness Difference
Ratio of Luminances (High Luminance Sq / Low Luminance Sq)
(c)
Lum.(Bkg.) / Lum.(High-Sq.)
1.09
1.41
1.62
1.95
Mean Lightness Difference
Contrast Ratio (High Contrast Sq / Low Contrast Sq
(d)

Figure 20

not of their contrasts (Figure 20d). In Figure 20c the results again all fell on the same function and are not distinguished.

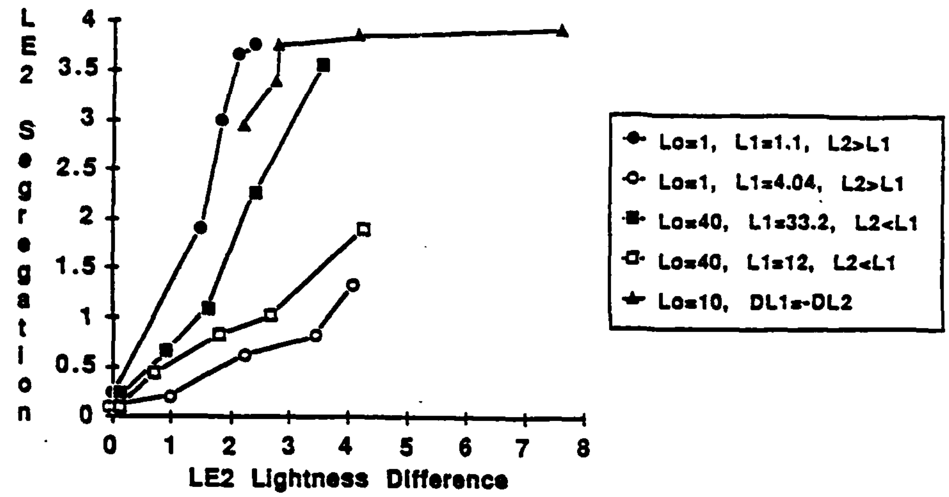
2.2.4 Experiment 2: Region Segregation--White, Gray and Black Backgrounds

Experiment 2 investigated the effects of varying the background luminance on the texture patterns used in Experiment 1. The light and dark squares composing a stimulus were presented on white, gray, and black backgrounds. On the white background, both squares were darker; on a black background, both squares were lighter, and on a gray background, the lightness of the background was between that of the squares.

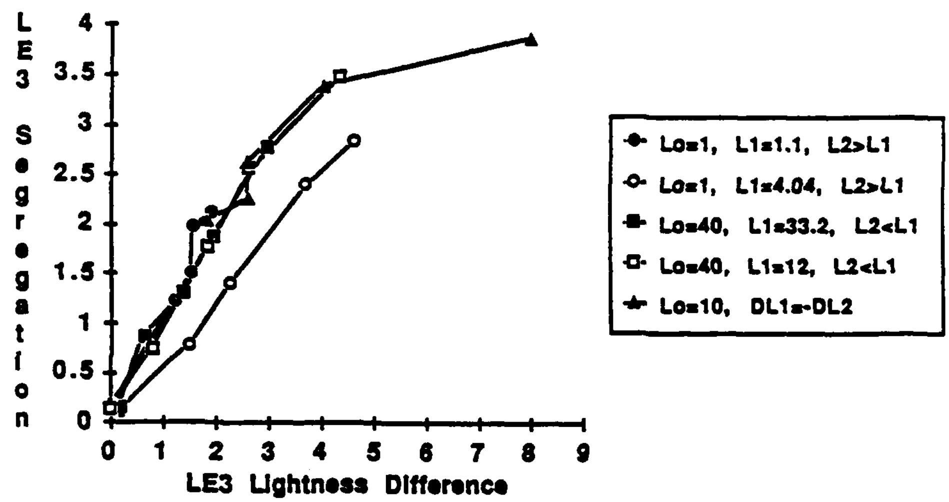
Stimuli.--Twenty-five stimuli were presented: ten each with a black and with a white background, and five with a gray background. With a black (0.99 ft.-L.) background, the luminance of the dark (lower-contrast, lower-luminance) square was fixed for five of the stimuli at 1.1 ft.-L., and for the other five stimuli at 4.04 ft.-L. When the dark square was 1.1 ft.-L., the luminances of the light (higher-contrast, higher-luminance) square were set at 1.10, 1.20, 1.25, 1.35, and 1.49 ft.-L. When the dark square was 4.04 ft.-L., the luminances of the light (higher-contrast, higher-luminance) square were 4.04, 5.00, 6.06, 8.06, and 11.10 ft.-L. With a white (40 ft.-L.) background, the luminance of the light (lower-contrast, higher-luminance,) square was fixed for five of the stimuli at 33.2 ft.-L. and for the other five of the stimuli at 12 ft.-L. When the light square was 33.2 ft.-L., the luminances of the dark (higher-contrast, lower-luminance) square were set at 33.2, 31.2, 29.2, 26.0, and 18.75 ft.-L. When the light square was 12 ft.-L., the luminances of the dark (higher-contrast, lower-luminance) square were set at 12.0, 8.7, 5.7, 3.8, and 0.0 ft.-L. With a gray (9.96 ft.-L.) background the two squares were of equal contrast and set above and below the luminance of the gray background by .5, 1.0, 1.5, 5.0, or 10 ft.-L.

Region Segregation.--Figure 21a shows perceived region segregation as a function of the lightness difference calculated from subjects lightness matches of the light and dark squares in a pattern. As in Experiment 1, equal lightness difference lead to different region segregation judgments depending on the relationship of the background luminance to the square luminances. For example, when the background was white, perceived segregation increased steeply with lightness differences when the luminance ratio of the background to the light square was 1.2 (filled squares). When the ratio of the background luminance to the light square was 3.3, (unfilled squares), strong texture segregation failed to occur with lightness differences of 3 and 4 steps. When the background was black, perceived segregation increased steeply with lightness differences when luminance ratio of the dark square to the background was 1.1 (filled circles). When the luminance ratio of the dark square to the background was 4.1 (unfilled circles) strong perceived segregation again failed to occur with lightness differences of 3 and 4 steps.

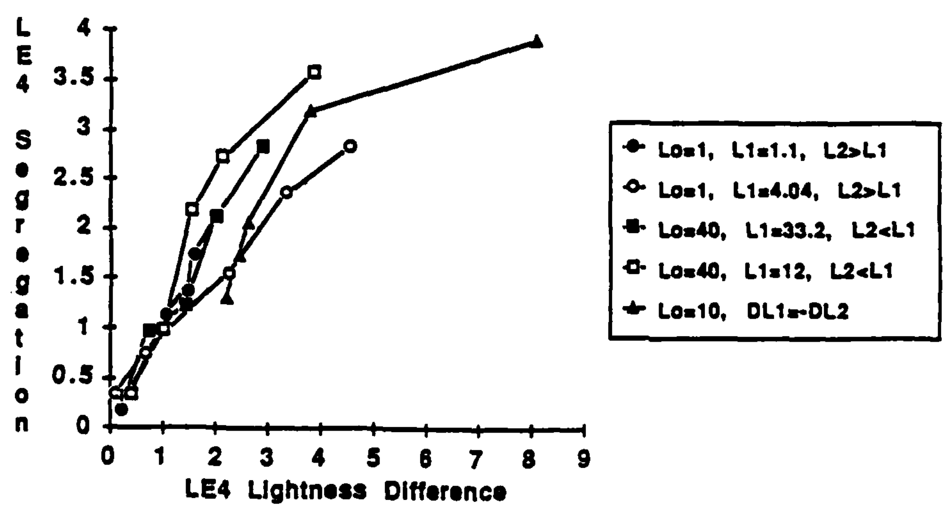
Figure 22a plots the rated segregations as a function of the ratio of the luminances of the light (high-luminance) and dark (low-luminance) squares. No single curve relates perceived segregation to the luminance ratios of the light and dark squares. The results with a white background are as in Experiment 1. For example, when the ratio of background luminance to the light square was 1.2 (triangles), perceived segregation increased sharply as a function of the luminance ratio of the light and dark squares. When the ratio of background luminance to the light square was 3.3 (+'s), perceived segregation remained weak with much larger luminance ratios of the light and dark squares. The results with a black background are like those with a white



(a)



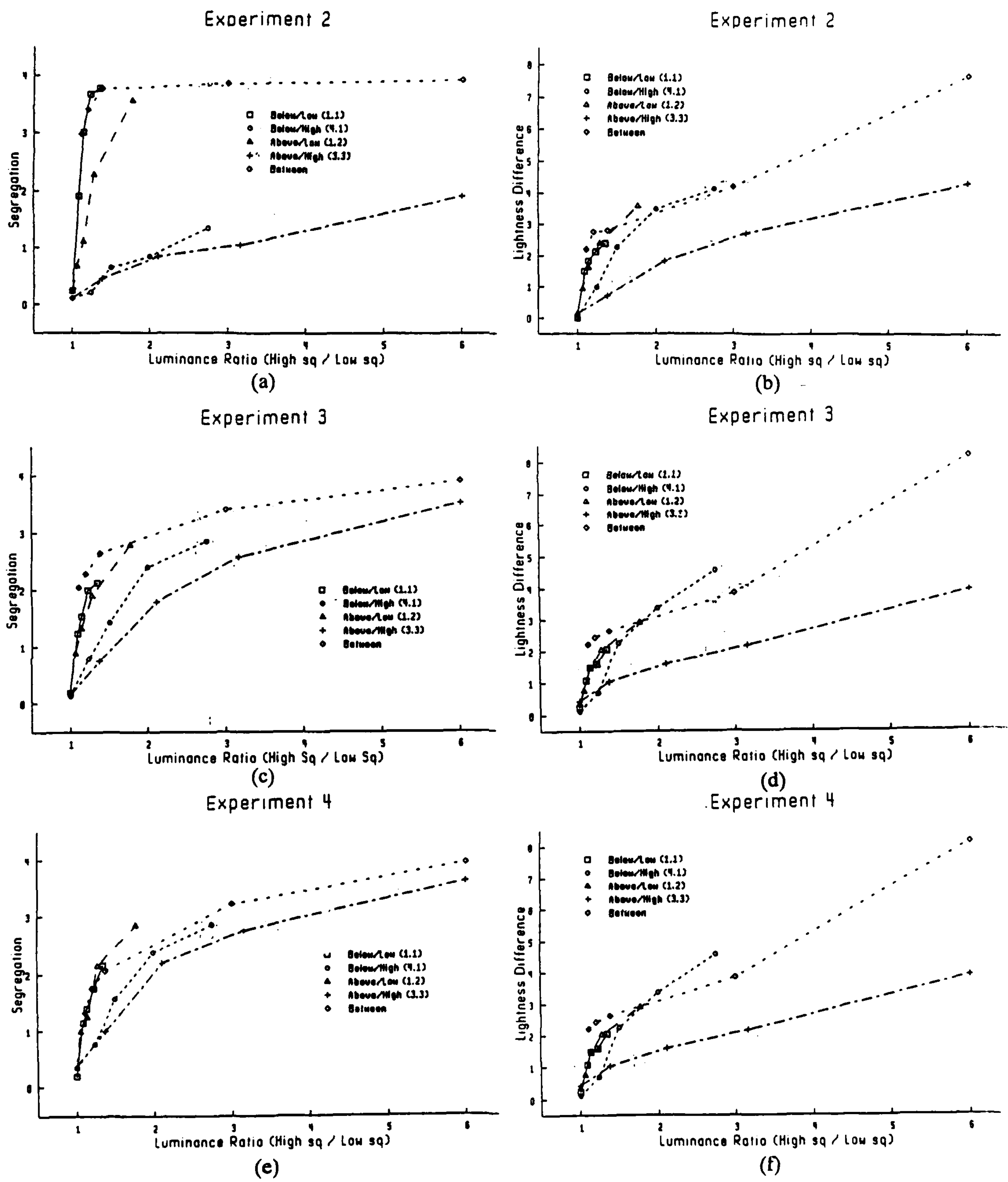
(b)



(c)

L_0=Background Luminance
L_1=Fixed Luminance
L_2=Variable Luminance

Figure 21



Experiment 2
Segregation
Luminance Ratio (High sq / Low sq)
(a)
Experiment 2
Lightness Difference
Luminance Ratio (High sq / Low sq)
(b)
Experiment 3
Segregation
Luminance Ratio (High Sq / Low Sq)
(c)
Experiment 3
Lightness Difference
Luminance Ratio (High sq / Low sq)
(d)
Experiment 4
Segregation
Luminance Ratio (High sq / Low sq)
(e)
Experiment 4
Lightness Difference
Luminance Ratio (High sq / Low sq)
(f)
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Between

Figure 22

background. When the ratio of the dark square to the background luminance was 1.1 (squares), perceived segregation increased steeply with increases in the luminance ratios of the light and dark squares. When the ratio of the dark square to the background luminance was 4.1 (circles), perceived segregation remained weak with large luminance ratios of the light and dark squares. As in Beck, Sutter, and Ivry (1987), perceived segregation was strong when the background luminance was between the luminances of the squares (a gray background) and decreased only when the luminance ratio of the light to dark square was 1.1 and 1.2 (diamonds).

Figure 23a plots perceived segregation as a function of the ratio of the contrasts of the light and dark squares. As in Experiment 1, perceived segregation tended to be a monotonic function of the contrast ratio of the light and dark squares. The results all fall along a single function except for the data points for a black background when the luminance ratio of the dark square to the background was 4.1. The failure for perceived segregation to increase with the increasing contrast ratio of the light to dark squares on a black background when the luminance ratio of the dark square to the background was 4.1 most probably reflects light adaptation processes. Studies of light adaptation indicates that the output from sensory processes compress for luminances that are far from the background luminance. The input to the channels should be the output from this nonlinearity, rather than the luminance of the squares.

Lightness Differences.--As in Experiment 1 and in Beck, Sutter & Ivry (1987), Figure 22b shows that the difference between the lightness matches was a single-valued function of the ratio of the luminances of the squares except when the background was white and the luminance ratio of the background to the dark square was 3.3 (+'s). In this condition, the lightness differences increased more slowly as a function of the ratio of the luminances of the light and dark squares. The reason for this unclear. The change in lightness as a function of the ratio of the luminance of a target to the background luminance is not the same under all conditions (Heinemann, 1989). The gain in lightness difference is controlled by the parameter k in Equation (1) which may vary with the experimental conditions. When k is small the difference in lightness increases more slowly with increases in the luminance ratio of the squares. In Experiment 1 the value of k of the best fitting logarithmic function is the same for all conditions. In Experiment 2, the functional dependence is more complicated. In Figure 22b, the values of k of the best fitting logarithmic function differed when the luminance of the background was 3.3 times the luminance of the light square from the other conditions. Figure 23b shows the lightness differences as a function of the ratio of the contrasts of the light and dark squares. As in Experiment 1, the data points fail to fall on a single line.

2.2.5 *Experiments 3 and 4: Populations--White, Gray and Black Backgrounds*

Experiments 3 and 4 studied the segregation of a display into two populations as a function of the lightness differences of the light and dark squares. The arrangement of the light and dark squares did not define two distinct spatial regions but were randomly distributed throughout the pattern (Figures 17a and 17b).

Stimuli.--The sizes of the squares and the luminances of the squares and of the backgrounds in Experiments 3 and 4 were the same as in Experiment 2. Figures 17a and 17b show the arrangements of the squares in Experiments 3 and 4 respectively. In Experiment 3, a stimulus consisted of 32 light squares and 24 dark squares. The displays were 300 x 350 pixels. The density of squares in Experiment 3 was much less than in Experiment 2. In Experiment 4, the density of

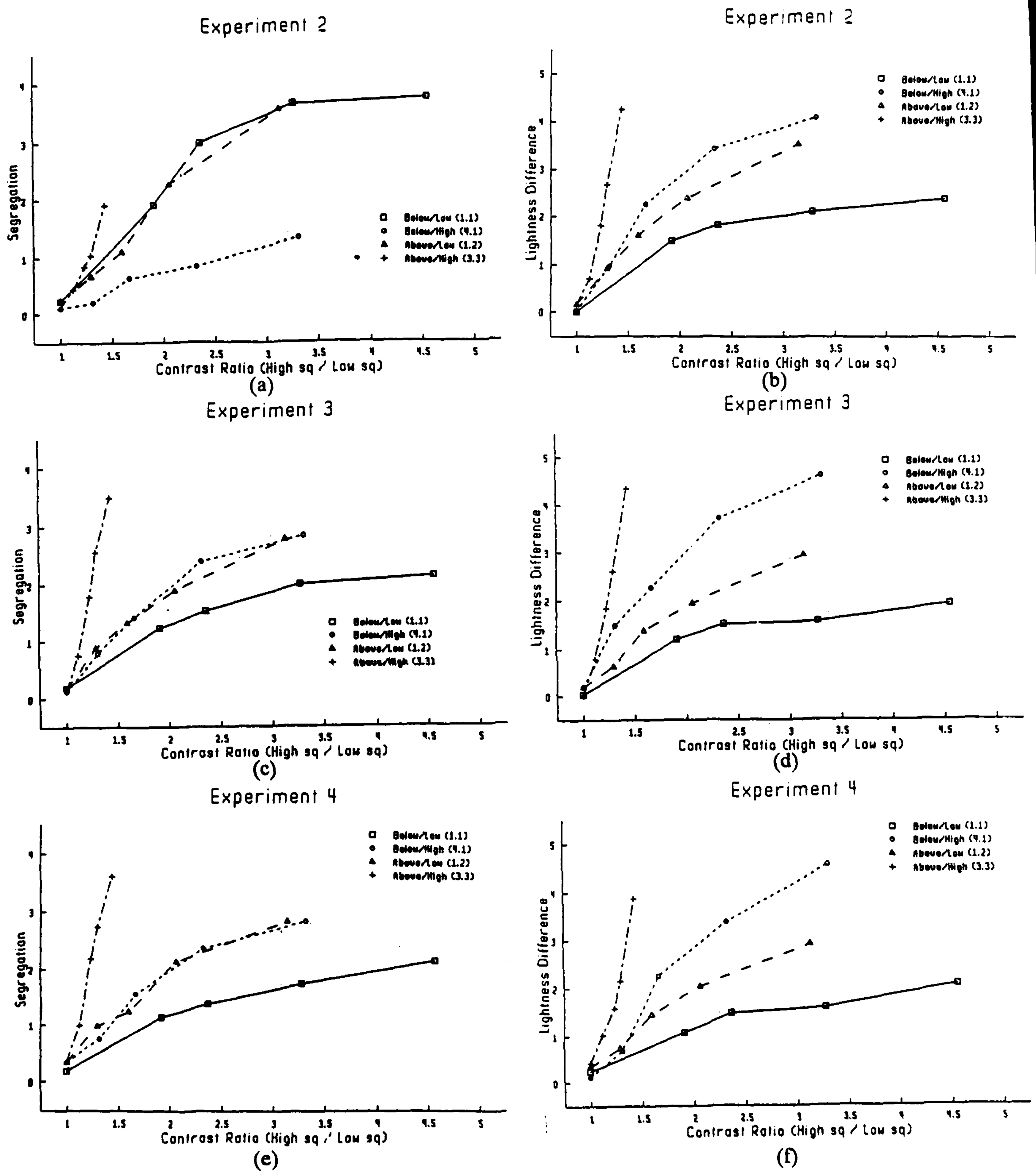

Experiment 2
Segregation
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(a)
Experiment 2
Lightness Difference
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(b)
Experiment 3
Segregation
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(c)
Experiment 3
Lightness Difference
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(d)
Experiment 4
Segregation
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(e)
Experiment 4
Lightness Difference
Below/Low (1.1)
Below/High (4.1)
Above/Low (1.2)
Above/High (3.3)
Contrast Ratio (High sq / Low sq)
(f)

Figure 23

squares was made more similar to the that in Experiment 2. The number of light squares was 41 and the number of dark squares 40.

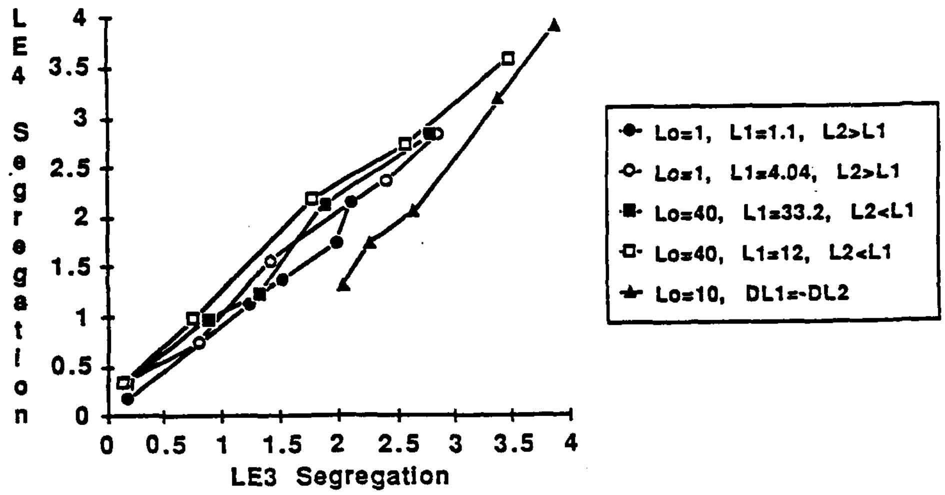
Population Segregation.--Perceived segregation as a function of the lightness difference of the squares is shown in Figure 21b for Experiment 3 and in Figure 21c for Experiment 4. A comparison of Figures 21b and 21c with Figures 21a and 19 shows that the scatter of segregation judgments is much less in Experiments 3 and 4 than in Experiments 2 and 1. These plots were fitted with the best fitting curve from a general family of monotonic functions known as asymptotic regression curves (Snedecor & Cochran, 1980). The proportions of the variance in perceived segregation accounted for by the lightness differences in Experiments 3 and 4 were .92 and .88 respectively. The proportions of the variance accounted for in Experiments 2 and 1 were less than .45. Lightness differences predict perceived segregation much better in Experiments 3 and 4 than in Experiments 2 and 1.

It is clear, however, that the population segregation ratings in Experiments 3 and 4 were not determined solely by the lightness differences. Systematic deviation from a single function can be seen in Figures 21b and 21c. Perceived population segregation as a function of lightness difference was greater in both Experiments 3 and 4 when the background was white and the ratio of the luminance of the background to the luminance of the light square was 3.3 (open squares) than when the background was black and the ratio of the luminance of the dark square to the luminance of the background was 4.1 (open circles).

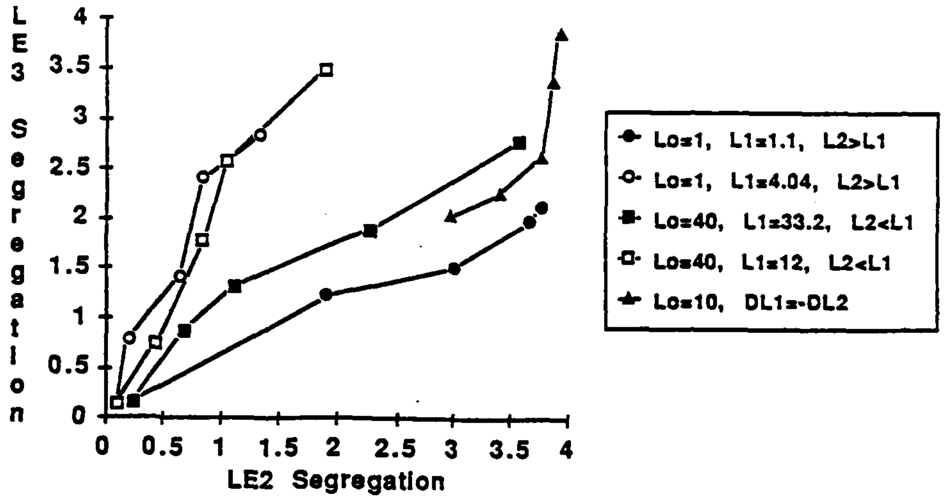
Perceived population segregation were highly similar in Experiments 3 and 4 but differed from those in Experiment 2. Figure 24a plots the segregation values in Experiment 3 against those in Experiment 4. The r^2 values between the segregation judgments in Experiments 3 and Experiment 4 is .94 (either fit linearly or nonlinearly). Figures 24b and 24c plots the segregation values in Experiments 3 and 4 against those in Experiment 2. They show considerable scatter. The r^2 values for a nonlinear monotonic fit between Experiments 2 and 3 and between Experiments 2 and 4 ranged between .56 and .66 and .42 and .50 respectively.

The segregation judgments in Experiments 3 and 4 as a function of the luminance ratio of the squares (Figures 22c and 22e) show less scatter than do the segregation judgments in Experiments 1 and 2. Unlike Experiments 1 (Figure 20b) and 2 (Figure 23a), where perceived segregation is to a first approximation a single valued function of the contrast ratios of the squares, perceived segregation in Experiments 3 and 4 is not a single valued function of the contrast ratios (Figures 23c and 23e). (The exception in Experiment 2 when the background was black and the luminance of the dark square was 4.1 that of the background can be explained by the loss of sensitivity due to light adaptation.)

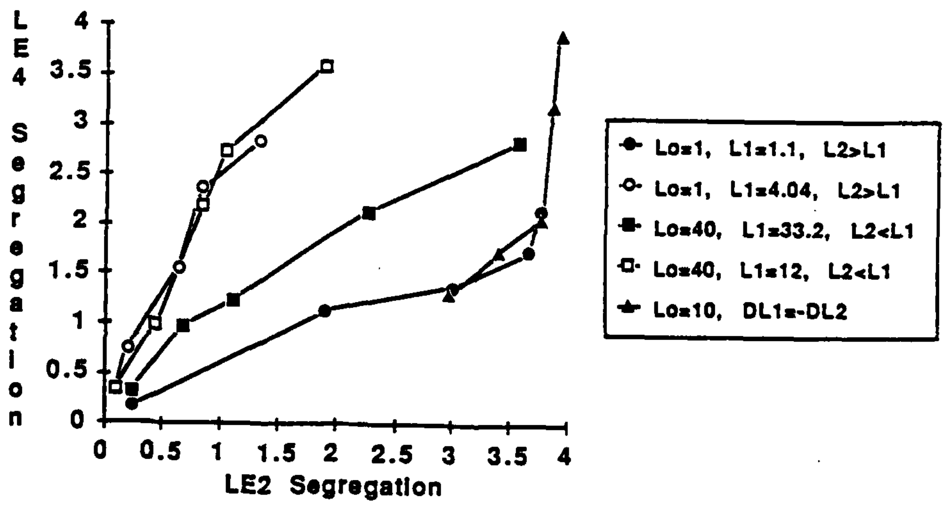
A comparison of the graphs in Figures 21 and 22 shows that perceived segregation in Experiment 3 (Figures 21d and 22b) and Experiment 4 (Figures 21f and 22c) is more nearly a single valued function of lightness differences than of luminance ratios. What is suggested is that the luminance ratios of the squares to the background in Experiments 3 and 4 did not uniquely determine the lightnesses of the squares; (as shown in Figures 22d and 22f) but that perceived population segregation and lightness are determined by the same factors.



(a)



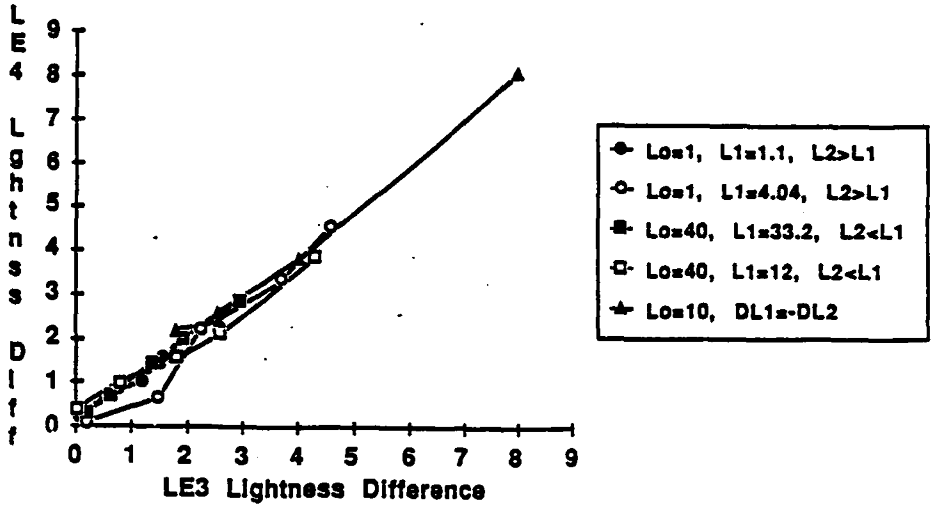
(b)



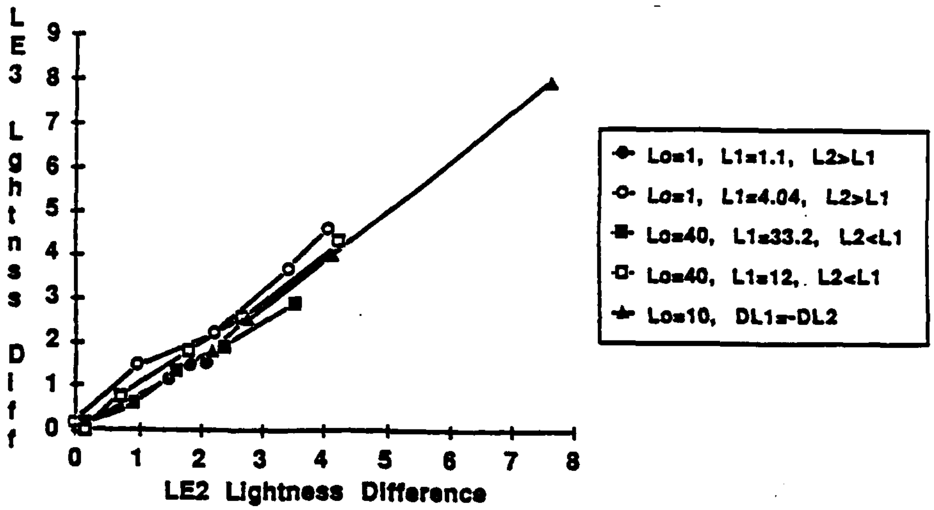
(c)

L_0=Background Luminance
L_1=Fixed Luminance
L_2=Variable Luminance

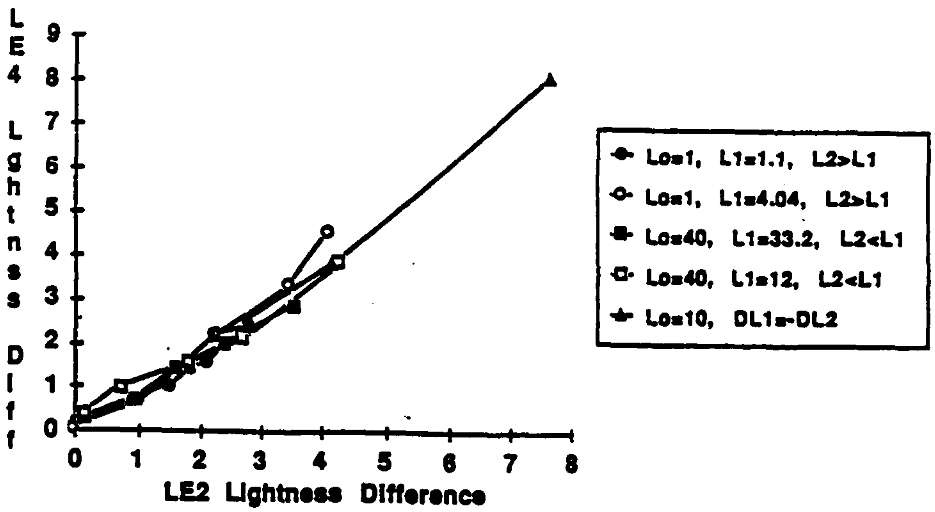
Figure 24



(a)



(b)



(c)

Figure 25

L_0=Background Luminance
L_1=Fixed Luminance
L_2=Variable Luminance

Lightness Differences.--The lightness matches in Experiments 3 and 4 are highly similar to those in Experiment 2 and to each other as can be seen in Figure 25 which plots the lightness differences in Experiments 2, 3, and 4 against each other. (Although only lightness differences are shown in Figure 25, it is also true that the lightness matches of the individual light and dark square were also highly similar.) The r^2 values between Experiments 2 and 3, Experiments 2 and 4, and Experiments 3 and 4 ranged between .97 and .98 for monotonic nonlinear fits. In Experiments 3 and 4, as in Experiment 2, lightness differences increased much less steeply as a function of the luminance ratio of the light and dark squares when the luminance of the background was 3.3 times the luminance of the light square.

2.2.6 *Discussion*

In summary, perceived lightnesses are much the same for given set of squares whether they are in texture regions (Experiment 2) in intermixed populations (Experiments 3 and 4). Perceived population segregation (Experiments 3 and 4) is highly correlated with perceived lightness differences but perceived region segregation (Experiments 1 and 2) is not. Perceived region segregation correlates with the ratio of the contrasts of the light and dark squares.

The tripartite pattern in Experiments 1 and 2 is a periodic patterns composed of approximately equal numbers of light and dark squares of equal size. Segregation of the pattern into regions depends on detecting the difference in the arrangement of the squares. The squares were arranged in a striped pattern in the top and bottom regions and in a checked pattern in the center region. The small bar detectors, spot detectors and edge detectors can provide no information for segregating the pattern into regions. These detectors can indicate that there are two populations--light and dark squares. There is, however, no spatial differentiation as a result of their outputs. The centroids of the populations of the light and dark squares are the same. The equal spacing of the squares also precludes proximity grouping or cluster detection. The detectors that do show strikingly different outputs to the different arrangement of elements in the striped and checked regions have larger receptive fields that are sensitive to the fundamental frequency of the texture region (Sutter, Beck, & Graham, 1989). They respond to the periodicity of the pattern and signal the differences in the overall pattern of squares in the striped and checked regions. In the striped region the changes of overall luminance occur in the direction of the X axis and in the checked region in a direction 45 degrees from the X axis. The activity of such cells correlates with the contrast ratio of the light and dark squares. The difference in arrangement of the light and dark squares in the striped and checked regions is not sufficient to yield strong region segregation when the relative contrasts of the light and dark squares are not sufficient to differentially stimulate channels sensitive to the fundamental spatial frequencies of the regions. The pattern does not segregate into three regions but into two subpopulations--light squares and dark squares. Sutter, Beck and Graham (1989) have reported similar results for squares differing in size. It is important to note that the perception of bimodality is subsidiary when the fundamental frequencies of the striped and checked regions are differentially stimulated. One sees then that there are three regions--stripes in the top and bottom and checks in the middle and that each region is made up of two types of elements. Our experiments indicates perceived region segregation to be approximately a single valued monotonic asymptotic function of the ratio of the contrasts of the light and dark squares as long as we avoid the nonlinearities introduced by light adaptation. (See Graham, Beck and Sutter, 1989, for more details of this description.)

The perceived segregation of patterns composed of two intermixed populations of light and dark squares (Experiments 3 and 4) is not a single valued function of the ratio of the contrasts of the light and dark squares (Figures 23c and 23e). Population segregation could not be due to differences in the responses of the large bar detectors; because the light and dark squares are distributed throughout the display, so the excitatory and inhibitory regions of the large bar detectors fall on both light and dark squares. The mechanism by which region and population segregation occurs is also different. In region segregation, the outputs from the spatial frequency/orientation channels are used to establish boundaries between the regions. In the population displays there are no boundaries. The population segregation of a display into light and dark squares is an example of pure similarity grouping. A plausible mechanism is to suppose that the visual system detects bimodality with respect to a feature such as lightness and divides the original population into two subpopulations. Unlike Experiments 1 and 2, perceived segregation in Experiments 3 and 4 is more like a single-valued function of the lightness differences of the squares (Figures 21b and 21c).

How the perceived lightnesses of the squares depends on the luminances of the squares and the background is not completely clear. Lightness has been taken to be a function of the ratio of the luminance of a stimulus and the adaptation level (Helson, 1964), or of the ratio of the luminance of a stimulus to the background (Wallach, 1948). One possibility is that the broad-band concentric cells found in blobs may compute the lightness of a surface (Livingston & Hubel, 1984; Ts'o & Gilbert, 1988). It has also been argued that the visual system responds only to contrast at its borders and that lightness is determined by the luminance ratio of edges (Land & McCann, 1971; Grossberg, 1987; Grossberg & Todorovic, 1988). The information for the perception of lightness is given by the odd-symmetric receptive fields which are thought to be involved in localizing edges and the small even symmetric receptive fields which would respond to the individual squares. The responses of these detectors to the light and dark squares would not be greatly affected by the differences in the arrangement of the squares in Experiments 2, 3, and 4. It is therefore not surprising that the lightness difference judgments (Figure 25) are similar in Experiments 2, 3, and 4.

The information computed in many models of lightness is the relative contrast of a surface (e.g., Shapley & Enroth-Cugel, 1985; Grossberg & Todorovic, 1988). That is, the Weber fraction-- the luminance increment of a surface divided by the average luminance of its surround. Lightness, on the other hand, appears to be a function of the relative luminance of a surface--the luminance of a surface divided by the luminance of its surround (Gilchrist & Jacobson, 1989; Jacobson & Gilchrist, 1988; Heinemann, 1989). How the visual system computes relative luminance is unclear? One possibility is that it adds the luminance of the surround to the increment luminance or it establishes an overall adaptation level that it adds to the increment luminance.

2.3 New Directions

This past year we began to take our research in new directions and to develop new research facilities.

2.3.1 *3D vs 2D*

An important problem is to characterize the perceptual features which result in the spontaneous and effortless segregation of patterns. Previous research with 2D perceived shapes found that texture segregation occurs strongly on the basis of simple physically defined features such as brightness, color, size and the slopes of contours and lines of the shapes. Differences in the spatial relations between features such as the arrangement of lines in a shape that leave the slope of the component lines the same do not generally yield strong texture segregation. Enns (1988) showed that this generalization does not hold for visual search when the shapes are seen to be three-dimensional. Parallel visual search was possible for targets and distractors equated for 2D features (eg. number and slopes of lines) that differed in their perceived 3D orientation. We have begun to investigate whether the 2D and 3D perceptions of a shape affect texture segregation.

We briefly present the results of one preliminary study. Figures 26 and 27 show displays in which the upper left quadrant is discrepant. As a 2D pattern, the Figures 26 and 27 differ only in the arrangement of their features and therefore should give similar segregation ratings. Ten subjects rated the segregation of the discrepant regions in Figures 26 and 27 on a scale from 0 to 4 when the patterns were flashed for 1 second. The mean segregation ratings were 2.4 for Figure 26 and 0.4 for Figure 27. The results are in accord with processing the shapes as 3D objects since three-dimensional objects in pictures are easier to apprehend when viewed from above. Figures 28 and 29 show displays in which the shapes composing the display are seen as two-dimensional. The mean segregation ratings were 1.4 for Figure 28 and .61 for Figure 29. These findings suggest that segregation in these textures is not based only on the 2D features of the projected image but also on the 3D representation of the projected image. If true, this has important implications for both physiological and computational models of early vision. We are pursuing this question.

2.3.2 *Research Facilities*

Our research has been performed on a Symbolics 3600 Lisp Machine with associated image processing and graphics hardware. During this past year, we purchased a Macintosh II computer to take advantage of its graphics capabilities. Our experimental research requires a large memory and a large screen display. We therefore also purchased an E-machines 19 inch color monitor and a 700 Megabyte Control Data hard disk. Our plan is to learn to program the Macintosh II using an object oriented language such as C++. During this coming year and the third year of the grant period, we hope to use the Macintosh II in addition to the Symbolics 3600 for experimental work. Although we have built up an extensive library of programs for the Symbolics 3600 which make it very valuable, it will become passe inevitably. We then plan to transfer our research to the Macintosh II system. The Macintosh II has already proven valuable for pretesting new patterns. We draw and modify new patterns using the Canvas paint program until we have the pattern we want. This has saved a great deal of programming time on the Symbolics 3600.

3. PUBLICATIONS (reporting AFOSR research, 1988-1989)

Beck, J., Rosenfeld, A. & Ivry, R. (1989). Line segregation. *Spatial Vision*, In press.

Beck, J., Graham, N. & Sutter, A. (1989) The effects of lightness differences on the perceived segregation of regions and populations. In preparation.

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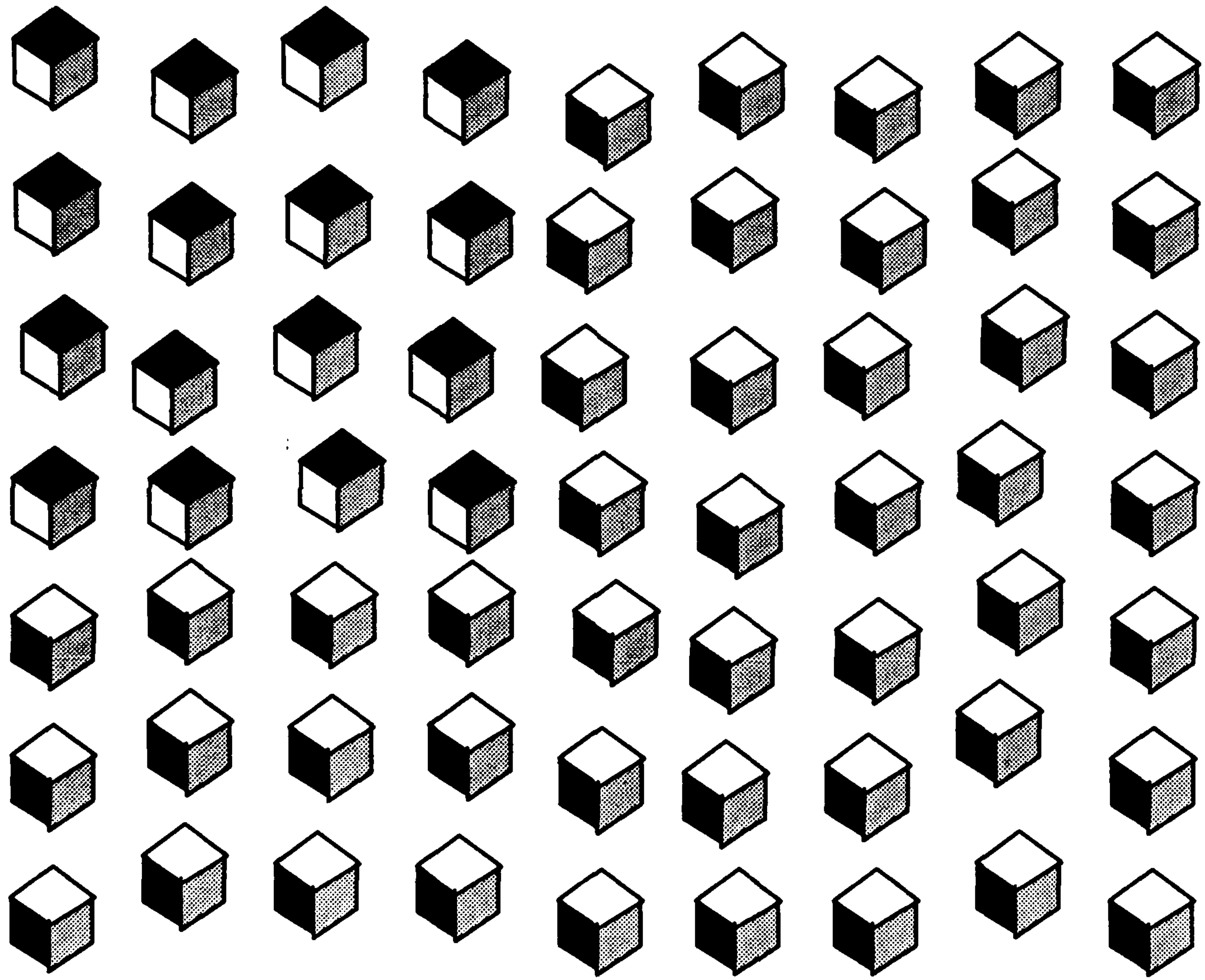

Figure 26

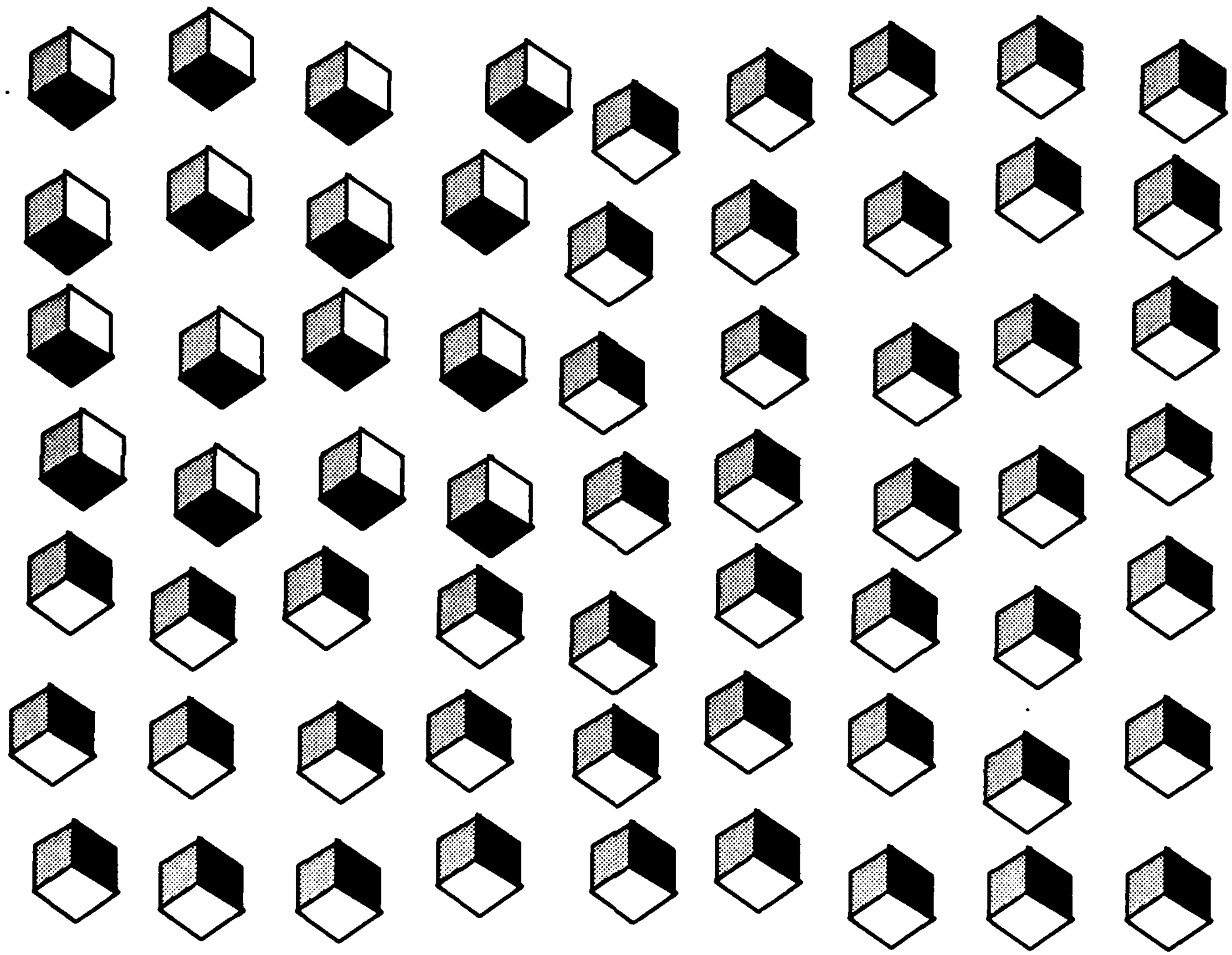

Figure 27

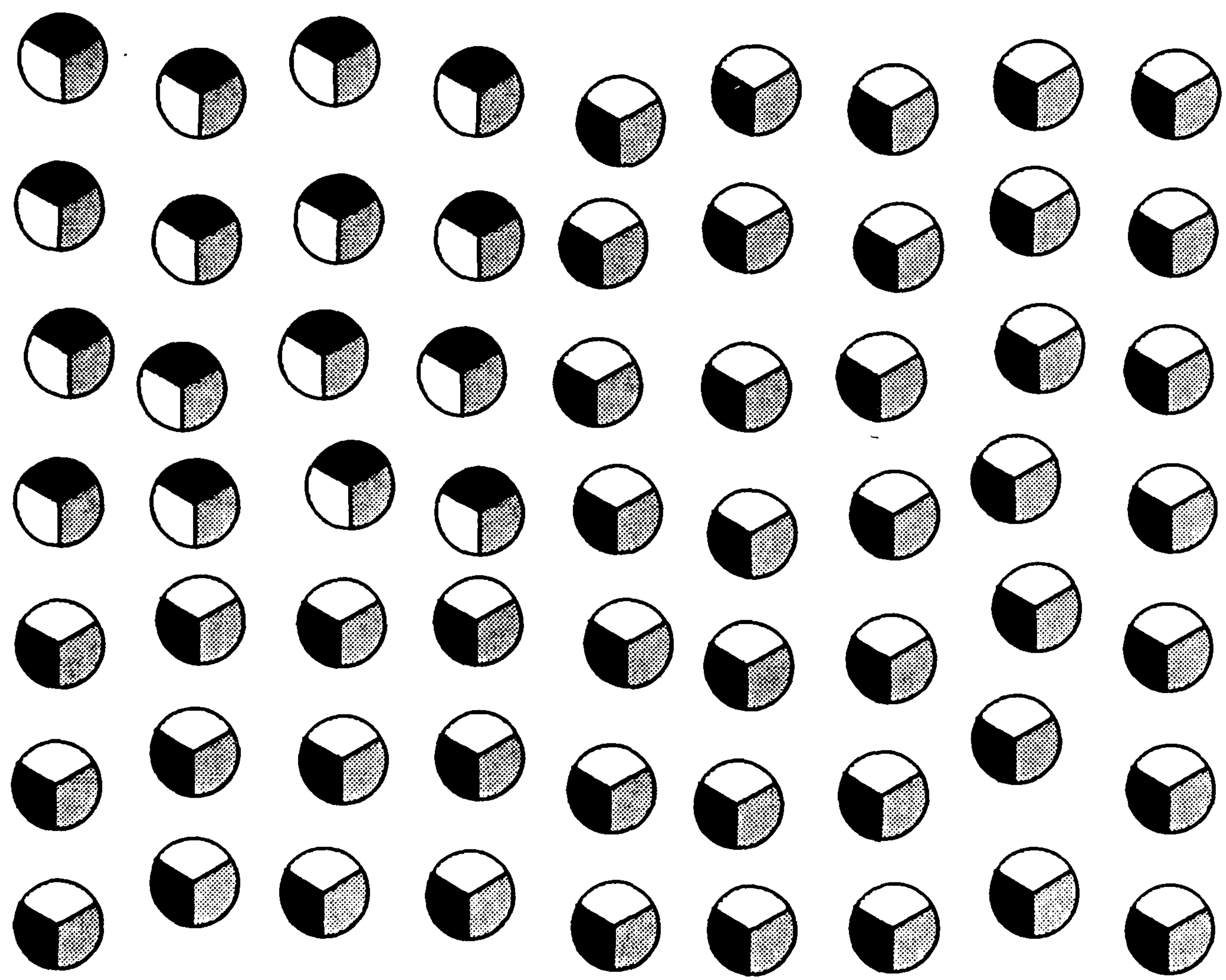

Figure 28

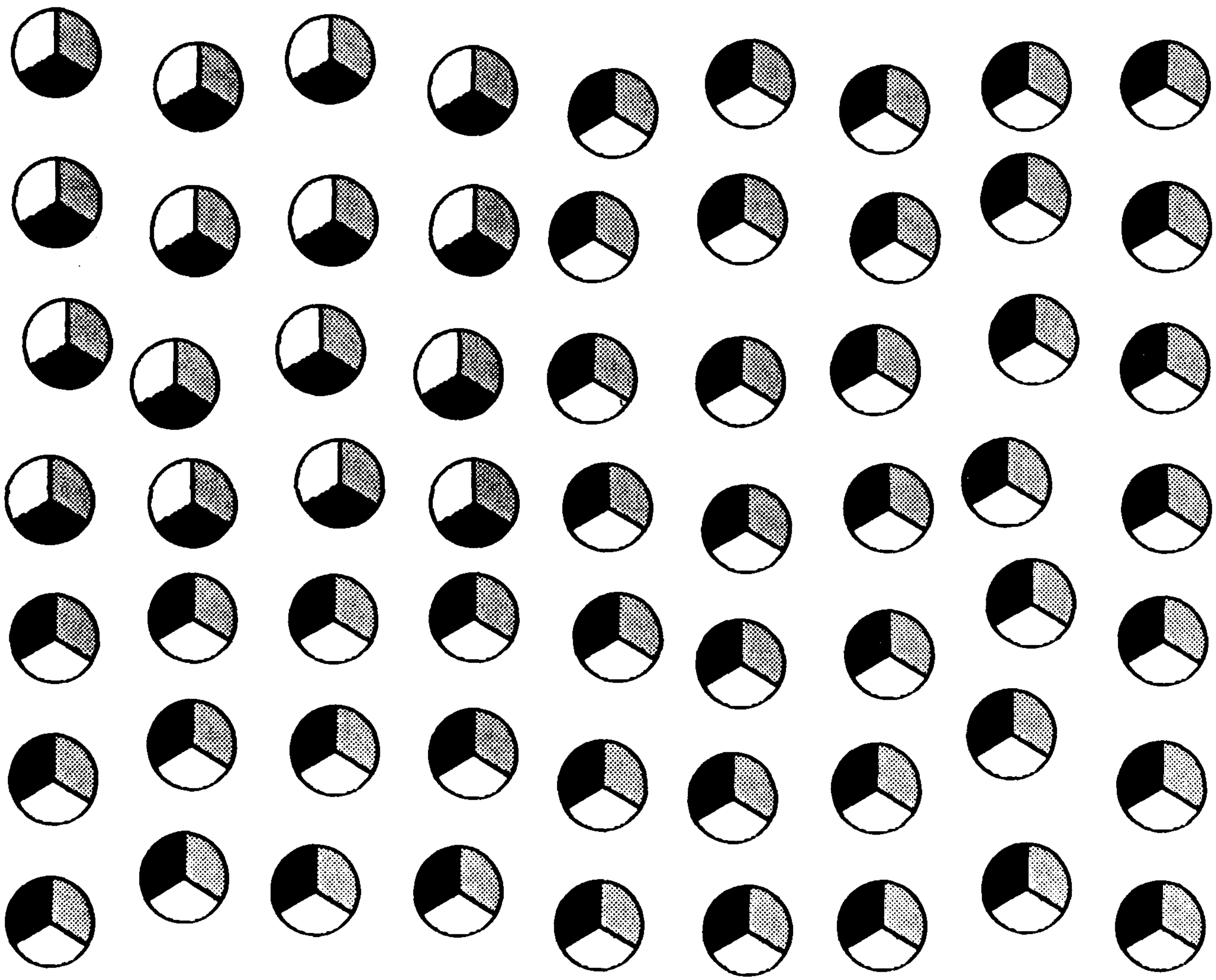

Figure 29

Graham, N., Beck, J., & Sutter, A. (1989). Contrast and spatial variables in texture segregation: testing a complex spatial frequency model. In preparation.

Sutter, A., Beck, J., & Graham, N. (1989). Contrast and spatial variables in texture segregation: testing a simple spatial-frequency channels model. *Perception & Psychophysics*, **46**, 312-332.

4. PROFESSIONAL PERSONNEL

Principal Investigator: Jacob Beck

Visiting Graduate Fellow (Madrid, Spain): Díana Perez

Programmer: Will Goodwin

Undergraduate students: Randy Hammond, Robert Graden

5. MEETINGS (reporting AFOSR research, *1988-1989*)

Twenty-ninth Annual Meeting of the Psychonomic Society, Chicago, Illinois, 1988, "Texture segmentation."

Fifth Human and Machine Vision Workshop, North Falmouth, Massachusetts, 1989, "Line segregation."

Twelfth European Conference on Visual Perception, Zichron Yaakov, Israel, 1989, "Two cases of preattentive segregation."

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